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BIOMECHANICAL ANALYSIS OF MILITARY BOOTS. PHASE I: MATERIALS TESTING OF MILITARY AND COMMERCIAL FOOTWEAR

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13. ABSTRACT *(Maximum 200 words)*

This is a report on Phase I of a two-phase analysis of footwear. In this phase military boots and commercially available boots and shoes were subjected to materials tests that included measures of impact, flexibility, stability, resistance of the outsole to accelerated wear, water penetration during immersion, and static and dynamic friction of the outsole. The military boots were the black leather combat boot and the hot weather boot. The commercial items were: a running shoe, a cross trainer, a work boot, a basketball shoe, a hiking boot, and a walking shoe. These items were not developed for use as military field footwear, but they incorporate materials and design concepts that could be adapted to a military boot. All footwear types were analyzed unworn and after having been worn for over 300 hours. The results indicated that the commercial running shoe and the cross trainer had impact properties superior to all other items. The running shoe was also the most flexible and took longest to reach the criterion of accelerated wear. The military boots showed good medial and lateral stability and the combat boot had good resistance to water penetration. The military and the commercial footwear had comparable coefficients of friction.

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Preface

The report on the biomechanical analysis of military boots and other footwear is the final report of Phase I of a two-phase project and was prepared under U.S. Army Natick Research, Development and Engineering Center contract DAAK60-91-C-0102. The work was performed at the Biomechanics Laboratory, Department of Exercise Science, University of Massachusetts, Amherst, MA, during the period September 1991 through July 1992. Dr. Carolyn K. Bensel was the project officer for the contract. Dr. Bensel is affiliated with the Human Factors Branch, Behavioral Sciences Division, Soldier Science Directorate. This project is part of the 6.2 program 1L162723AH98AAOGOO (Aggregate Code T/B1368) -- Biomechanical Approach to Soldier-CIE Integration, which is being carried out by Dr. Bensel and other members of the Human Factors Branch.

The authors gratefully acknowledge the technical assistance of the following graduate students in the Department of Exercise Science: Theresa Foti, Tim Derrick, Jill Crussemeyer, Greg Lange, Sharon Fuller, and Debbie King. The authors also wish to express their appreciation to Ms. Marcia L. Lightbody of the U.S. Army Natick Research, Development and Engineering Center for her valuable editorial comments and support in the preparation of this report.

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Biomechanical Analysis of Military Boots.
Phase I: Materials Testing of Military and
Commercial Footwear

Introduction

The most widely issued footwear in the Army and the Marine Corps is a particular type of boot that is designated for use in training, garrison, and field environments when specialized footwear (e.g., safety shoes, cold weather boots, hot weather boots) is not needed. Male and female recruits receive this boot at the beginning of their basic military training and use it for almost all activities that comprise "boot camp". Recruits are sometimes permitted to wear commercial sport shoes, which they bring with them from home or purchase after arriving for training. The sport shoes are worn only to a limited extent, generally for portions of the formal physical training program, such as daily calisthenics and runs, although these activities may also be performed in the boot. After completing basic training, military men and women continue to wear the boot for physical training, field exercises, in their garrison work environments, and on the battlefield.

There have been a number of generations of this footwear, each differing from the others in design and material composition. The latest version was introduced into the military inventory in the mid-1980s. This boot, commonly referred to as the "combat boot", has a leather upper with a padded collar. The outsole is direct molded to the upper and has a deep lug design. The boot is issued with a removable, urethane foam insert that has a fiberboard backing and extends from the heel to the toe of the boot.

The latest combat boot was the result of a development effort that began in the early 1980s at the U.S. Army Natick Research, Development and Engineering Center (Natick). The direction of the development effort was guided by requirements, or performance criteria, that were generated by Army and Marine Corps organizations responsible for identifying the characteristics that materiel must embody if it is to meet the needs of military personnel. The military wanted a boot that enhanced the locomotor capabilities of the wearer, minimized the occurrence of lower extremity problems, and was comfortable. Other requirements pertained to weight, height, design of the closures, camouflage characteristics, water-resistance, durability, storage life, military appearance, and outsole composition. Still other requirements dealt with cost of the item, production rate, and production capabilities within the United States. Indeed, much is demanded of the footwear, and the boot reflects the attempt to accommodate a range of requirements at a relatively low cost.

In addition to the combat boot, there is another boot that is frequently worn by many Army and Marine Corps personnel, although this boot is not as widely used as the combat boot. The second footwear item, which was developed during the 1960s for use in Southeast Asia, is commonly referred to as the "jungle boot". This boot is now prescribed for use in hot-humid climates, but soldiers are given the option of wearing it in other climates should they so choose. Like the combat boot, it is worn for physical training, field exercises, in garrison, and on the battlefield. The jungle boot is fabricated of leather in the foot portion and has a cotton/nylon duck upper. The boot has a direct molded sole with a lug tread and a steel plate incorporated into the insole. Like the combat boot, the jungle boot is issued with a removable insert. As was the case with the combat boot, development of the jungle boot was guided by requirements of the military users. For example, the upper is made of duck because of a requirement for the boot to dry quickly; eyelets are in the arch area because some means for water to drain out of the boot was required; and the steel plate serves a requirement for protection of the foot from puncture by spikes embedded in the ground.

The strong interest of the public in physical fitness over the last 15 or 20 years, and the attention paid by footwear manufacturers to producing shoes for this market, has stimulated research into materials and construction processes for athletic footwear. Much of this research has been in the realm of sport biomechanics (Cavanagh, 1980; Nigg, 1986b). Goals of the biomechanics research done on athletic footwear include enhancing the locomotor performance of the wearer and reducing the incidence of lower extremity injuries (Cavanagh, 1980; Nigg, 1986b). There is evidence that progress has been made in achieving these goals (Cavanagh, 1980; Nigg, 1986a). Although the military services also have an interest in enhancing the locomotor performance of personnel and reducing lower extremity injuries (Bensel, 1976; Bensel and Kish, 1983), findings from biomechanical studies have not been employed in the development of military boots.

One outcome of the public's focus on physical fitness, and the footwear industry's responses to it, is that, today, the consumer is faced with a wide selection of shoes for just about every popular athletic activity. There has also been an impact, to a limited extent, on the footwear available for various occupations that involve physical activity. The situation in the civilian sphere is unlike that in the military; a single type of military footwear, such as the combat or the jungle boot, must be appropriate to wear for a wide variety of activities (e.g., running, climbing, crawling, marching, jumping) on a wide range of surfaces and terrains. In addition, as discussed above, there are many considerations influencing the design of military boots that are not germane to footwear for civilian uses.

In spite of the differences between military and civilian applications in terms of demands placed upon footwear, the goals of enhancing the wearer's performance and reducing lower extremity injuries are vitally important in both domains. Insofar as it leads to achieving these goals, biomechanics can contribute to development of military footwear, as it has to development of footwear for the civilian market. However, biomechanics has not had a role in military footwear research; it appears that biomechanical testing was performed on military footwear only once. The work was conducted in the early 1980s by deMoya (1982) and involved a predecessor to the present combat boot.

Given the lack of information about the biomechanical properties of current military boots and the potential for improving the boots in the future through application of biomechanical principles, a research program focusing on the biomechanical analysis of military footwear was established. The long-term objective of the research is to develop, from the data acquired, a series of recommendations for future military footwear with regard to materials, design, construction, fabrication techniques, and any other features that would benefit the performance and the lower extremity health of military personnel, particularly ground troops. The research is divided into two phases, with the first phase consisting of materials testing and the second of human user testing. The results of the first phase of the research, the materials testing phase, are reported here.

The methods used for testing the footwear materials were originally derived from standard, mechanical tests used in other industries (Beckwith, Buck, and Marangoni, 1982). The most publicized materials tests of sport shoes were conducted by Dr. Peter Cavanagh at the Pennsylvania State University Biomechanics Laboratory. Cavanagh's work was done in conjunction with the annual shoe survey published in Runner's World magazine. The work involved the application of laboratory tests to quantify physical characteristics thought to be important in the design and construction of running shoes. In the survey, Cavanagh initially used tests to assess heel and forefoot shock absorption, upper and sole durability, and flexibility (Cavanagh, 1978). Later, the number of tests was increased to include assessments of rearfoot control, traction, water vapor permeability, and effects of repeated impacts (Cavanagh and Williams, 1981).

There is, unfortunately, a dearth of standard test methods to use in the mechanical testing of footwear. The American Society of Testing and Materials (ASTM) has convened committees to formulate such standards, but little has been accomplished in this area. Therefore, although they have not been part of the shoe survey in Runner's World since 1981, many of the laboratory tests used by Cavanagh are still used today by the sport shoe industry to evaluate prototype and existing shoes. The testing procedures now employed, and those used in the research presented here, generally follow Cavanagh's closely, with some modifications in testing machinery and protocols.

The question has been raised in the biomechanical community as to whether materials tests yield data that relate to the functioning of individuals performing in the footwear (Bates, 1985). This question is open to debate. The human/footwear system is a complex biomechanical unit with performance characteristics that may be unique to an individual, whereas materials tests assume a commonality across individuals' functional needs. However, materials tests are more reliable, less time-consuming, and less costly than human user testing of footwear (Cavanagh, 1980; Nigg, 1986b). There is general agreement that materials tests alone are inappropriate but serve an important purpose when complemented by human testing (Cavanagh, 1980; Frederick, Clarke, and Hamill, 1984; Nigg, 1986b). Used in this manner, materials testing can be a screening device to identify, out of a large array of footwear items, those particular items embodying features worthy of further study in human testing. Also, the physical characteristics of a footwear item are specified through materials tests. This information is needed to understand the results of human user tests of the item and to convert the results into improvements in the item.

Two types of military footwear were studied in the present research, the combat and the jungle boots. These boots were selected because they are general-purpose footwear items and are widely used throughout the Army and the Marine Corps. A total of six types of commercial sport shoes and work boots was also studied, being subjected to the same testing conditions and protocols as the military footwear. The commercial items were not developed for use as military field footwear. However, they do incorporate materials and design concepts that could, with modifications, be adapted to a military boot. The testing of the commercially available footwear also serves to generate data against which to assess the findings for the military footwear. Comparative data are important in footwear materials testing because there are no acceptable or unacceptable scores on the tests in terms of avoidance of injury when wearing a shoe. Although each test yields a quantitative index, the relationship between the index and the probability of injury associated with use of the footwear has not been established (Cavanagh, 1985).

Aging of footwear, and associated degradation of material properties, is a major concern in developing boots for military personnel. Before being issued, the footwear must withstand years of storage under extreme environmental conditions without deteriorating. Once in use, the footwear must withstand up to 180 days of continuous wear in military field situations without requiring replacement. The effects of aging on the physical properties of sport shoes are also a concern (Cavanagh, 1980). Hamill and Bates (1988) found that running shoes may lose 10% of their shock attenuation ability after exposure to 240 km of running. To address the issues of wear and aging in the present study, the footwear was tested new, in an unworn state, and after having been worn outside the laboratory over an eight-week period.

The procedures and the results of the materials tests carried out on the footwear are presented in this report, along with conclusions that relate to findings on performance of the military boots. A separate report will describe the human testing phase of this two-phase research program applying biomechanical techniques to military footwear. The human testing, which is now underway, comprises a study of the effects of military and commercial footwear on the locomotor patterns of men and women.

Footwear

The two types of military boots tested were sizes 5 and 9 in a Regular width. The six types of commercial shoes and boots were sizes 7 and 9 in a standard width. Each type of footwear studied is described and pictured below. The photographs include a cross-sectional view of each item. Durometer readings to measure hardness of the midsoles of each type of footwear are included as part of the item descriptions. These data represent means obtained from readings taken five times at each of several sites on the midsole of a footwear item.

Combat Boot

The official nomenclature for this footwear, pictured in Figure 1, is: Boot, Combat, Mildew and Water Resistant, Direct Molded Sole. The upper, which is unlined, is fabricated of chrome tanned, grain-out, cattlehide leather, treated for mildew and water resistance. The upper has a rigid box toe, made

Figure 1. Three views of the combat boot.

of Surlyn®, a one-piece, combined backstay and counter pocket, and a padded collar. The heel counter is made of leatherboard. The boot closure system is a combination of eyelets and closed loops. The rubber outsole has a deep lug design, designated as the Trac Shun pattern. The outsole is direct-molded to the leather insole using a method of vulcanization. A zinc-coated steel shank extends from the middle of the heel through the arch and ends just back of the ball area. The boot has a removable Poron® insert that extends from heel to toe. The insert is made of a closed-cell, urethane foam with a fiberboard backing. The mass of a pair of boots, in a size 9, is 1.86 kg. The height of a boot in a size 9, measured from the heel breast to the top of the collar, is 26.0 cm. The durometer of the midsole was 85 on a Shore A scale.

Jungle Boot

The official nomenclature for this footwear is: Boot, Hot Weather, Type I, Black, Hot-Wet. The boot is pictured in Figure 2. The upper, which is unlined, is fabricated of leather in the foot portion and along the length of the closure system;

Figure 2. Three views of the jungle boot.

the rest of the upper is made of a textured nylon Cordura®. Two screened eyelets are set in the leather on the medial side of the boot, in the arch area. Their purpose is to facilitate drainage of water in instances in which the boot may have been submerged. A 2.54-cm wide, nylon tape runs up the back and around the collar of the upper. There is also a 5.08-cm wide, nylon webbing stitched diagonally across the ankle. The upper has a rigid box toe of Surlyn, the same material used in the combat boot. Like the combat boot, the heel counter in the jungle boot is made of leatherboard. The removable, Poron insert is the same as that used in the combat boot. The closure system is a combination of eyelets and closed loops. The rubber outsole is patterned after heavy treads on military vehicles and is referred to as the Panama design. The outsole is direct-molded to a leather insole. The leather insole is split into two pieces and a 0.28-cm thick, stainless steel plate is inserted between the pieces and stitched around the periphery. The plate extends the entire length of the boot. As is the case with the combat boot, the jungle boot has a zinc-coated steel shank extending from the middle of the heel to just in back of the ball area. A pair of jungle boots in a size 9 has a mass of 2.01 kg. The height of the boot in a size 9, measured from the heel breast to the top, is 23.5 cm. The durometer of the midsole, measured on a Shore A scale, was 84.

Nike Air Max

This running shoe is pictured in Figure 3. The upper is a perforated synthetic with a sculpted, external ankle collar. The midsole contains an air sole, encapsulated full length in polyurethane. The outsole is a waffle design with flex grooves cut in the forefoot area. The insert of this shoe is a contoured, soft foam covered with a sockliner material. A pair of these shoes in a size 9 has a mass of 0.80 kg. The height of the shoe in a size 9, measured from the heel breast to the top, is 10.7 cm. The durometer of the midsole, measured on a Shore A scale, was 65.

Figure 3. Three views of the Nike Air Max.

Nike Cross Trainer

This is a multipurpose, athletic training shoe. It is pictured in Figure 4. The upper is constructed of perforated synthetic mesh quarter panels and has a cut-away, exoskeleton design heel counter. The shoe also has a forefoot arch-strapping system. The midsole is a full-length, Phylon® foot-frame. The outsole has a modified waffle design with flex grooves cut in the forefoot area. The insert, a soft foam covered with a sockliner material, is contoured to provide arch support. A pair of shoes in a size 9 has a mass of 1.10 kg and the height of a shoe, measured from the heel to the top of the upper is 12.1 cm. The durometer of the midsole measured 55 on a Shore A scale.

Figure 4. Three views of the Nike cross trainer.

Red Wing Work Boot

This is a work boot, structurally similar to the combat boot. The item is pictured in Figure 5. The Red Wing has a water-repellent, full-grain leather upper sewn to a stiff, rubber, unidensity midsole. The upper has an insulating lining throughout. In the midsole, there is a tempered steel shank extending from the heel to the arch area. The outsole is made of rubber in a Vibram® pattern and is a Goodyear welt construction. The insert is composed of a soft foam covered with a soft felt. The insert is not removable. The mass of a pair of size 9 boots is 1.50 kg. The height of a boot in a size 9, measured from the heel breast to the top, is 21.4 cm. The durometer of the midsole measured 85 on a Shore A scale.

Figure 5. Three views of the Red Wing work boot.

Reebok Pump

This is a basketball shoe that incorporates the "pump" technology for the purpose of enhancing shoe fit. The shoe is pictured in Figure 6. The upper is constructed of "tumbled" leather. The midsole is composed of Hexalite® in conjunction with polyurethane. The outsole is made of rubber. The insert, which is glued to the midsole, is a soft foam covered with an absorbent sockliner material. The mass of a pair of shoes in a size 9 is 1.26 kg and the height of a size 9 is 15.4 cm, measured from the heel to the top. The durometer of the midsole measured 60 on a Shore A scale.

Figure 6. Three views of the Reebok Pump.

Rockport Hiking Boot

This boot, which is pictured in Figure 7, has a leather upper with an internal Gore-Tex® bootie. It has a hand-sewn, moccasin construction and an internal, Hytrel® heel counter. The midsole is made of an ethyl vinyl acetate (EVA) and the outsole is a special, slip-resistant rubber compound. The insert consists of sockliner material on top of a contoured foam base. A pair of size 9 boots has a mass of 1.50 kg and the height of a size 9, measured from the heel breast to the top of the upper, is 13.1 cm. The durometer of the midsole measured 55 on a Shore A scale.

Figure 7. Three views of the Rockport hiking boot.

Rockport Walking Shoe

This shoe has an all-leather upper with a padded collar. The shoe is pictured in Figure 8. The midsole is constructed of a

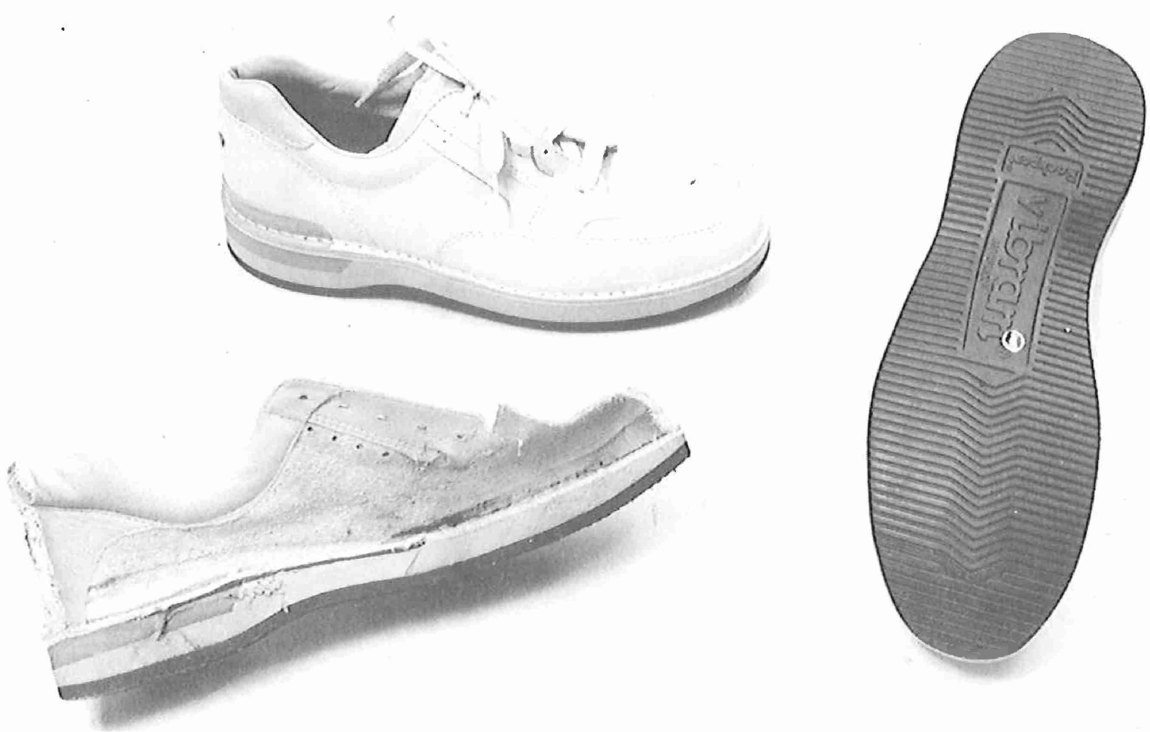

Figure 8. Three views of the Rockport walking shoe.

dual-density layer of EVA foams and the outsole is an abrasion-resistant rubber compound made by Vibram. The insert is sockliner material on top of a contoured foam base. The mass of a pair of size 9 shoes is 0.90 kg and the height of a size 9, measured from the heel to the top, is 10.4 cm. The durometer of the midsole measured 65 on a Shore A scale.

Method

Footwear Samples

All footwear included in this study was procured from open stocks of the items; no footwear was produced specifically for this investigation. Six pairs of each type of footwear (three pairs in each of two sizes) were subjected to the materials tests. The military boots were sizes 5 and 9 in a Regular width. The commercial shoes and boots were sizes 7 and 9 in a standard width. Two pairs of each size were tested new, in an unworn state. Each member of a pair was subjected separately to the entire testing process. Thus, data for the unworn footwear were obtained from eight samples (four pairs) of each footwear type. The third pair in each size was tested after having been worn outside the laboratory for a period of time. Thus, data on the used footwear were obtained from four samples of each footwear type. The procedure employed in exposing the footwear to use is presented below.

Testing Procedures

Six tests were performed on the unworn and the worn footwear. For a given test, one experimenter collected the data on all the unworn and the worn footwear. All testing was conducted in the Biomechanics Laboratory at the University of Massachusetts-Amherst. The temperature and humidity conditions in the laboratory were those of a normal laboratory environment, and otherwise uncontrolled.

Impact Test

An Exeter Research Impact Tester (Exeter Research, Brentwood, NH) was used to assess impact and rebound. This instrument is designed to test footwear according to proposed, but not yet adopted, ASTM standards. It consists of a metal shaft, or missile, that slides freely in the vertical plane. The missile head attached to the metal shaft is a solid, metal cylinder, 10.2 cm long, with a diameter of 4.5 cm. The shaft and the missile head have a combined mass of 3 kg. Another mass is added to the top of the shaft to obtain a drop mass of 8 kg. The drop height of the missile is set at 5 cm. The footwear being tested is held in place below the shaft by a DeStaco clamp. The impact test instrument is computer interfaced and samples at 1000 Hz via an A/D converter. The computer controls the missile drop height and the number of impacts, or drops. A linear variable differential transducer (LVDT) and a Kistler accelerometer return the data on each drop of the missile to the computer via the A/D converter.

In the context of the human/footwear system, the impact tester is intended to mimic the foot hitting the ground at foot strike. The following parameters are measured directly or derived from those that are:

Peak g (in multiples of the acceleration due to gravity). This is the maximum acceleration of the missile head upon impacting the shoe. In terms of the human/footwear system, peak g is used as an index of the vertical force occurring at initial contact of the foot with the ground. The contact results in an impulsive force that, during running, may be two to three times greater than the human's body weight (Cavanagh and LaFortune, 1980; Clarke, Frederick, and Cooper, 1983a). In the impact test, peak g is interpreted as a reflection of the shock-absorbing capabilities of the shoe, with lower values indicating better shock absorbency (Cavanagh, 1980).

Time to peak g (in ms). This is the time from first contact of the missile head with the shoe to achievement of maximum deceleration. It is also referred to as rise time. The higher the value on this measure, the lower is the rate of change of the impact force. In terms of the human/footwear system, a lower rate of change of the impact force indicates a slower deceleration of the foot as it contacts the ground and, thus, less of a jolt to the body (Clarke et al., 1983a). Longer times to peak g on the impact test are thought to indicate better cushioning in the shoe (deMoya, 1982).

Maximum penetration (in percent). This is the amount by which the missile penetrates the shoe material, expressed as a percentage of the total thickness of the shoe at the site of impact. Maximum penetration is interpreted as an indication of the amount by which the foot would sink down into the surface of the shoe upon impact with the ground. Higher scores, or greater penetrations, are interpreted as indicating better shock-absorbency of the footwear at impact (Bates, Sawhill, and Hamill, 1980).

Peak pressure (in N/cm^2). This is the force per unit area exerted on the shoe by the missile head at the time of maximum acceleration. Peak pressure is derived from peak g on a given trial and two known constants, the mass of the missile and its head dimensions. There is a direct and positive relationship between peak pressure and peak g. Therefore, as is the case for peak g, lower values of peak pressure indicate better shock absorbency.

Coefficient of restitution (a dimensionless measure). This is the negative ratio of the relative velocity after impact to the relative velocity before impact. It is also referred to as rebound. The higher the coefficient of restitution, the greater the amount of kinetic energy conserved upon impact. A coefficient of 1 indicates a perfectly elastic impact, whereas a coefficient of 0 indicates a completely inelastic impact. In terms of the human/footwear system, the less energy lost upon impact, the less internal energy the human must use to propel the body into the next step (Clarke et al., 1983a). In footwear materials testing, the coefficient of restitution is used as an index of the cushioning properties of the footwear with higher values indicating better cushioning (deMoya, 1982).

Energy return (in percent). This is the coefficient of restitution multiplied by 100. The energy return parameter serves to emphasize the fact that 100% of the kinetic energy is conserved in a perfectly elastic impact and 0% of the energy is conserved in a completely inelastic impact. As is the case for the coefficient of restitution, higher energy return values indicate better cushioning of the footwear (deMoya, 1982).

Prior to conducting the impact test, the uppers of the footwear samples were cut away, leaving the insert, midsole, and outsole of each sample intact. In the cases of those items that had removable inserts, the impact test was conducted with the inserts in place. The test was done on two sections of each footwear sample, the forefoot and the heel. Each of the two sections was subjected to 25 preliminary impacts, immediately followed by 10 test impacts. Data on the parameters described above were recorded during each of the test impacts, but not during the preliminary impacts. This cycle of preliminary impacts followed by test impacts was done three times on each section of a footwear sample. For each parameter, a mean was calculated over the data for the 30 test impacts on the forefoot. Likewise, means were calculated over the 30 test impacts on the heel.

Flexibility Test

This test was carried out on a specially designed flexion machine, modelled after that used by Cavanagh (1978). The device has two platforms connected by a hinge. One platform is fixed and the other is movable. The middle and the rear parts of the shoe are clamped to the movable platform; the forepart is mounted on the fixed platform. The forepart is secured to the platform by inserting a flat, metal plate in the forefoot and using a clamp with a load of 136 kg to press down on the metal plate. The shoe is positioned relative to the two platforms such that a point 40% of the shoe length, as measured back from the toe, is aligned with the hinge between the platforms. During the test, flexion occurs at the part of the shoe aligned with the hinge. This site is selected because high-speed films of humans running in running shoes have shown that the maximum flexion of the shoe occurs at about 40% of the shoe length from the toe (Cavanagh, 1980).

A load cell is mounted on the device to measure the force of the resistance to movement of the movable platform. Movement of the movable platform is accomplished by a torque motor. The motor displaces the movable platform at a set rate from 0° through 43°. The maximum displacement is comparable to the maximum achieved during human gait (Inman, 1976). A potentiometer is mounted to the hinge between the two platforms in order to measure angular displacement. Because shoes commonly have a natural flexion at the forefoot of about 10° and must be stretched to achieve a flexion of 0°, force measures are taken only during the period of flexion from 10° to 43°. The output of the load cell is proportional to the instantaneous force applied by the motor to displace the movable platform. The output of the cell is fed to an IBM-386 microcomputer, which performs on-line calculations of the force required to produce the change in angle. This is expressed in N/degree.

Flexibility is considered to be an important parameter influencing the human/footwear system. The less flexible the footwear, the more force the muscles of the foot and leg must apply to bend the shoe in order to propel the body into the next step. Therefore, the less flexible the footwear, the more the muscles may be stressed (Cavanagh, 1980). Lower values on the flexibility test indicate lower forces required to bend the forepart of the footwear and, thus, better flexibility in the footwear.

In this study, the footwear was tested in two configurations: with the item intact and with the upper removed. In each configuration, testing of the footwear samples was done in three, successive stages. First, a sample was subjected to 50 preliminary flexes followed immediately by a test period comprised of 45 flexes. Then, there were 2000 more preliminary flexes followed by another test period of 45 flexes. The number of flexes up to this point approximates the number of times, on the average, that a shoe would be flexed over the course of a 5-mi run (Bates, James, and Osternig, 1978). Finally, after 10 min had elapsed since the last flex, the sample was subjected to another test period of 45 flexes. Data were acquired only during the three test periods, and a mean was obtained over the 45 flexes making up a test period. Thus, for each footwear sample, there were three means for the intact configuration and three for the configuration with the upper removed.

Stability Test

This test is performed on the medial and the lateral borders of the heel of the footwear. The footwear is intact for this testing. The device used consists of two, hinged platforms. One platform is fixed and the other is movable. The shoe is placed on the platforms such that 1.27 cm of the heel portion lies on the movable platform and the rest of the shoe lies on the fixed platform. The shoe is held in place on the fixed platform by a clamp that exerts a force of 136 kg on the rearfoot portion of the shoe. The movable platform is displaced through a range of 25° by a crank attached to a torque motor. The movement compresses the sole at the heel border. A load cell measures the force necessary to displace the movable platform; a potentiometer, located at the hinge between the two platforms, measures the angular distance moved.

The voltage outputs from the load cell and the potentiometer are routed through an A/D converter interfaced to an IBM-386 microcomputer. The voltage outputs are then converted to newtons of force and degrees of angular distance. The dependent measure, stability, is calculated as the slope of the force-angular distance curve over the 25° range. Stability is expressed in N/degree.

Like the flexibility test, the stability test can be viewed as a measure of material stiffness. In the case of the flexibility test, the forepart of the shoe is assessed; in the stability test, the focus is on the medial and the lateral borders of the shoe in the heel area. Cavanagh (1980) applied the stability test to the medial border only and used it as a reflection of rearfoot control. This measure is the extent to which a shoe will resist compression, in effect remain stable, during the early support phase of running, thus limiting the amount or rate of subtalar joint pronation.

After the landing impact at initial contact of the foot with the ground, there is pronation within approximately the first 50% of foot contact, followed by supination until take-off (Clarke, Frederick, and Hamill, 1984). Pronation of the subtalar joint consists of simultaneous eversion, abduction, and dorsiflexion. Supination involves the reverse movements of inversion, adduction, and plantar flexion (Hlavac, 1977). Although the movements of the subtalar joint act to decrease peak forces experienced by the leg after foot strike, excessive pronation has been linked to running-related injuries, particularly those of the knee (Clarke et al., 1984). Harder midsoles have been found to decrease the amount of pronation and rearfoot movement during running (Cavanagh, 1980; Clarke, Frederick, and Hamill, 1983b). Therefore, higher values on the stability test, indicating greater forces required to compress the midsole, reflect better rearfoot control in the footwear.

In this study, a footwear sample was subjected to 30 successive trials on the medial border of the heel and the same number on the lateral border. A mean was obtained over the trials on each border to represent the stability of the sample.

Sole Wear Test

The outsole wear procedure is modelled after the wear test used by Cavanagh (1978). The shoe is fixed over an abrasive belt in a position representative of foot strike for a runner (15° eversion, 30° abduction, and 10° dorsiflexion). A specially designed jig maintains this position in which the rear outside border of the heel is closest to the abrasive surface. The shoe is loaded with a mass of 3 kg to ensure that contact is maintained between the shoe and the belt. The belt is moved past the shoe, at a speed of 2.2 m/s, for periods of 15 s. The outsole is measured after each period. To take the measurement, the shoe is placed on a horizontal surface with the highest, or thickest, part of the outsole resting on the surface. The distance from the surface to the lowest, or thinnest, part of the outsole is then measured as an index of the depth to which the outsole has been penetrated. Testing of the shoe sample is terminated when the measurement equals or exceeds 1.9 cm. The score on the test is the total time required to achieve the penetration of 1.9 cm, expressed in 15-s increments.

Obviously, the higher the score on the sole wear test, the better from an economic standpoint. However, the decreases in outsole thickness with wear can also be associated with reduction in the shock-absorbing properties of the footwear. In addition, sole wear can change the alignment of the foot and leg during ground contact, possibly resulting in lower extremity injury (Cavanagh, 1980).

Water Penetration Test

In this test, the shoe is mounted on a footwear last that is instrumented with water-sensitive electrodes. Two electrodes are located in the forefoot area of the last: one on the superior surface and one on the inferior. Two other electrodes are placed in the rearfoot area of the last: one on the inferior surface of the heel and one on the medial surface, immediately below a level corresponding to the medial malleolus of the foot. The footwear is submerged in water for approximately 15 min to a level just above the electrode mounted on the medial surface of the last. Each electrode is sampled once every 15 s throughout the immersion period. The measure on this test is the length of time until water is first detected at any one of the four electrode sites. In those cases in which water is not detected during the immersion period, a score equal to the total time of immersion is assigned.

The water penetration test used in this study is unlike the method employed in the Runner's World shoe survey (Cavanagh and Williams, 1981). In that shoe survey, a test of the permeability of the shoe upper to water vapor was used as an index of the ease with which sweat can pass through the upper materials to the outside environment. Higher scores indicated better permeability. The water penetration test used here was a measure of the ease with which water can pass from the outside environment into the footwear. Higher scores indicate better resistance to water penetration. It was judged more appropriate to use a water penetration method in this study because military personnel must often work in wet environments where water intrusion can precipitate serious foot problems (Orr and Fainer, 1952).

Friction Test

There are many mechanical methods and types of apparatus used to test friction between a shoe and a surface, and no one approach is universally accepted (Strandberg, 1983). In this study, the frictional characteristics of the outsoles of the footwear items were tested using a towed-sled procedure similar to that proposed by Irvine (1967) and evaluated by Andres and Chaffin (1985). For this procedure, a Chatillon gauge with a known normal force of 98.1 N is employed. The portion of the footwear being tested is bolted to the underside of a sled having a mass of 10 kg and the gauge is connected to the sled. The gauge is pulled manually along a horizontal surface at a constant velocity of 1 cm/s. A static coefficient of friction (COF) is calculated from the pull force at the point of movement and a dynamic COF is calculated from the pull force during the constant motion. The higher the COF, the greater the resistance of the footwear item to slipping.

The footwear items were tested on five different surfaces. These were asphalt, carpeting, cement, natural grass, and vinyl tile. Each surface was used under four treatment conditions: dry (untreated), wet, oiled, and greased. The outsole of the footwear was cleaned with soap and water before being exposed to each surface and treatment combination. Only portions of a footwear item were subjected to the friction test. These were a heel section and a forefoot section cut from the shoe; the two sections were tested separately. The heel section was the rearmost one-third of the total length of the shoe and the forefoot section was the foremost one-third. Each section was towed from a static position 10 times on a given combination of surface and treatment. A mean static COF and a mean dynamic COF were calculated over the 10 trials for each footwear sample.

In the Runner's World shoe survey, Cavanagh and Williams (1981) used a James Machine to measure friction. The arm of the machine first presses down vertically on the footwear sample and then gradually changes its orientation until it pushes the sample to the point of slipping. The apparatus employed by Cavanagh and Williams (1981), like that used in the present study, involves movement straight ahead at a constant speed, such as that seen in walking or running. When a human is moving in this manner, a higher COF between the footwear and the surface is desirable in order to avoid slipping (Cavanagh and Williams, 1981). Neither a minimum static nor a minimum dynamic COF has been established below which slipping is highly probable. Indeed, the level of friction adequate to maintain the stability of the human varies with stride length (James, 1983). However, a number of researchers have cited static and dynamic COFs of 0.30 as being the lowest acceptable levels (Cavanagh and Williams, 1981; Perkins and Wilson, 1983). In terms of a maximum COF, it has been stated that values greater than 0.80 may constitute a trip hazard (R. O. Andres, personal communication, February 1992).

Rotational movements, where the foot must rotate around a point of contact between the shoe sole and the surface, were not examined in the Runner's World survey (Cavanagh and Williams, 1981) or in this study. However, it may be that a lower COF is desirable when rotational movements are being performed in order to avoid torques on the lower extremities that may lead to injuries (Frederick, 1986).

Testing of Footwear Worn Outside the Laboratory

As mentioned previously, unworn samples of each type of footwear were subjected to the testing procedures described above and samples were also tested in the same manner after having been used outside the laboratory for a period of time. Two pairs of each footwear type, one pair in each of two sizes, were used outside the laboratory. These footwear samples were not tested in an unworn state as well.

Eight men and eight women participated in the wear process. The men used the larger and the women the smaller footwear sizes. Each individual was asked to wear one pair of footwear at least five hours per day for five successive days. This pair of shoes was then passed on to another individual who also was to wear it for five days. This process continued until each pair of footwear had been used for five days by eight men or eight women. The individuals were asked to keep a daily journal of activities performed while wearing the footwear.

Results

Visual examination of the data from each test revealed highly similar scores for the two sizes that were used in each type of footwear. Therefore, size was not treated as an independent variable, and a simple one-way analysis of variance (ANOVA), of the form Samples within Footwear, was carried out on each of the dependent measures. The data for the unworn and the worn samples were analyzed separately. For the unworn items, the number of samples equalled eight and, for the worn items, the number of samples equalled four. The significance level for the analyses was set at $p<.05$. In those instances in which the main effect of footwear was found to be significant, Tukey's honestly significant difference (HSD) procedure was applied as a post-hoc test.

As discussed previously, there are no acceptable or unacceptable scores on a given test in terms of avoidance of injury when wearing a particular type of footwear (Cavanagh, 1985). Thus, the results of the materials tests can best be assessed by comparing the scores for the various types of footwear. The findings on each test are presented below. Information related to the unworn footwear is presented first. Information pertaining to the worn footwear follows at the end of the section. The results of the statistical analyses are presented in tabular form in Appendices A and B for the unworn and the worn footwear, respectively. Included in a table are descriptive statistics for each type of footwear, the value of the F-ratio, and, where appropriate, the outcome of the HSD procedure.

Impact Test

Forefoot and heel impact data for the footwear tested in an unworn state are presented in Tables A-1 and A-2, respectively. Low values of peak g and peak pressure and high values on the remaining four parameters are considered to reflect better performance of the footwear on this test.

Comparing the results from the forefoot and the heel areas, it can be seen in Tables A-1 and A-2 that the peak g and the peak pressure recorded in the heel portion of the footwear items were lower than those recorded in the forepart. This finding applied to the military as well as to the commercial footwear. With respect to maximum penetration, the heel portion of the commercial items yielded lower values than the forefoot did. For the combat boot, the values were the same and, for the jungle boot, the maximum penetration reading for the heel was higher than that for the forefoot. In terms of time to peak g, some of the commercial items had higher values for the heel than for the forefoot, whereas others had lower values. The combat boot had shorter times to peak g for the heel than for the forefoot and the jungle boot had longer. With regard to the coefficient of restitution and its related parameter, energy return, the findings among the commercial items were again inconsistent; some of the items had higher values for the forepart than for the heel, whereas others had lower. For both the combat and the jungle boots, the values for the forefoot were higher than those for the heel.

The analyses of the forefoot and the heel data yielded a significant main effect of footwear on each of the six parameters measured on the impact test. The Tukey _HSD_ procedure indicated that the relationships among the footwear means varied somewhat across the parameters. However, the footwear can be divided into three groups on the basis of the overall findings on the impact test measures. The groupings are:

1. combat boot and jungle boot;
2. Red Wing, Reebok Pump, Rockport hiking boot, and Rockport walking shoe;
3. Nike Air Max and Nike cross trainer.

In ascending order of the groupings, the footwear in the previous group tended to have higher peak g readings, shorter times to peak g, lower maximum penetrations, higher peak pressures, lower coefficients of restitution, and lower energy return values. This finding applied to both the forefoot and the heel data.

The _HSD_ post-hoc procedure indicated some overlapping of the groups to the extent that all footwear types in the second group were not significantly different from those in the first or in the third groups on all measures. In addition, for the coefficient of restitution and the energy return values measured on the forefoot, the mean for the Nike Air Max was not significantly different from the means for the combat or the jungle boots (Table A-1). With these exceptions, the footwear in the first and the third groups did differ significantly on all measures (Tables A-1 and A-2).

Some of the differences between the combat and the jungle boots and the Nike Air Max and the cross trainer were substantial. The maximum penetration means for the two military boots were less than half those for the Air Max and for the cross trainer, and the mean peak pressures for the military boots were approximately twice those for the two commercial shoes. Also, the combat boot had the highest mean values of peak g at both the forefoot and the heel and these values were more than double the lowest mean values, those for the Nike cross trainer. Similarly, mean time to peak g measured at the heel of the combat boot was less than half that for the cross trainer.

With regard to the relationship between the two military boots, there was only one measure which yielded a significant difference between them. This was the peak g of the forefoot. On this measure, the mean for the combat boot was higher than the means for all other footwear types.

Of the commercial footwear items, the Red Wing yielded results most similar to those for the military boots when all impact measures made on the forefoot and the heel are considered. However, on several measures, including peak g, maximum penetration, and peak pressure, the mean values for the Red Wing differed significantly from those for both the combat and the jungle boots.

Flexibility Test

The flexibility data for the unworn footwear items are presented in Table A-3. Lower values on this test are desirable because they indicate lower forces required to bend the forepart of the footwear. All types of footwear tested were more flexible with the upper removed than with the upper intact. Also, there was a decrease in the stiffness of most footwear types as the number of flexes was increased, regardless of whether or not the upper had been removed. The exceptions were the combat boot, the Reebok Pump, and the Rockport walking shoe. With the uppers intact, these items yielded somewhat higher values after 2095 flexes than they did after 50 flexes. When flexed again after a 10-min interval had elapsed since the previous flex, the footwear items generally showed an increase in stiffness relative to the values after 2095 flexes, but the values tended to remain lower than those obtained after 50 flexes.

All analyses performed on the flexibility data yielded a significant main effect of footwear. In each case, the Tukey HSD procedure revealed that the Red Wing had significantly higher stiffness values than the other types of footwear (Table A-3). When tested with the upper in place, the means for the jungle boot were higher than those for all other footwear types, except the Red Wing. However, when the upper was removed, the jungle boot yielded among the lowest values for stiffness. The data collected with the upper in place also yielded relatively high stiffness values for the combat boot; the means for the combat boot differed from those for the jungle boot only in the data acquired after 50 flexes. The Nike Air Max, followed by the Reebok Pump, had relatively low values, regardless of whether or not the upper was in place.

Stability Test

The results of the stability testing performed on the medial and the lateral borders of the unworn footwear are presented in Table A-4. In this test, higher values are associated with the more stable footwear, reflecting better rearfoot control. With the exception of the Red Wing, the values obtained from the medial border of the footwear were somewhat higher than those obtained from the lateral; the opposite occurred with the Red Wing.

In terms of the relative stability of the various types of footwear tested, the ANOVA performed on the data for the medial border yielded a significant main effect of footwear, as did the ANOVA on the data for the lateral border (Table A-4). The combat boot, followed by the jungle boot, had the highest stability values for the medial border. The HSD post-hoc tests revealed that the mean for the combat boot, although not significantly different from that for the jungle boot, was significantly higher than the values for all other footwear types. The mean for the jungle boot was also not significantly different from the means for the Red Wing or the Rockport hiking boot. The Reebok Pump and the Rockport walking shoe had the lowest stability values in the testing of the medial border, but they did not differ significantly from the values for the Nike Air Max or the Nike cross trainer.

In the stability testing of the lateral border, the combat boot again had the highest mean value. However, the mean for the boot did not differ significantly from the mean for the Red Wing, which, in turn, did not differ significantly from the mean for the jungle boot. As was the case for the medial border, the lowest stability values for the lateral border were associated with the Reebok Pump and the Rockport walking shoe. The post-hoc tests revealed that the mean for the Reebok Pump was significantly lower than all means except that for the Rockport walking shoe. The values for the walking shoe also did not differ significantly from those for the Nike Air Max or the Nike cross trainer.

Sole Wear Test

The results of the sole wear test carried out on the previously unused footwear are in Table A-5. The data presented are the times required, in 15-s increments, to achieve a 1.9-cm penetration of the outsole, with higher scores reflecting better performance. The analysis of variance again yielded a significant main effect of footwear.

The _HSD_ post-hoc procedure showed that the Nike Air Max, which was one of the least stiff types of footwear as measured on the flexibility test, took significantly longer to reach the criterion level of wear than the other items did. This was followed by the Reebok Pump, the other type of footwear that was found to be relatively low in stiffness. The post-hoc tests of the sole wear data also revealed that the combat boot, the Red Wing, and the Rockport walking shoe, which did not differ from each other, reached the criterion significantly faster than the other types of footwear did.

Water Penetration Test

The findings from the water penetration test performed on the unworn footwear are presented in Table A-6. A significant main effect of footwear was again obtained. The post-hoc tests revealed that the footwear items with all-leather uppers had similar means; these items remained dry throughout the immersion period. On the other hand, the two types of footwear that had cloth in the uppers, the jungle boot and the Nike Air Max, had means significantly lower than the means for the all-leather items. The jungle boot and the Air Max evidenced leakage of water into their interiors after less than 1 min and after approximately 3 min of immersion, respectively.

The jungle boots were subsequently retested after the eyelets that are set in the leather in the arch area had been plugged. Under this condition, water did not penetrate into the jungle boot during approximately 15 min of immersion.

Friction Test

The results of the friction testing performed on the unworn footwear under the 20 combinations of surfaces and surface treatments are presented in Tables A-7 through A-26. With few exceptions, the static and the dynamic COFs were 0.29 or higher, which is at and above the minimum cited to avoid slipping. The exceptions occurred mainly on the cement and the vinyl tile surfaces treated with oil or with grease (Tables A-17, A-18, A-25, and A-26). With these surface/treatment combinations, COFs as low as 0.10 were obtained.

Comparisons of the data from the heel and the forefoot sections do not reveal that one section consistently yielded higher COFs across the eight types of footwear tested (Tables A-7 through A-26). However, for the combat boot, there was a tendency for the COFs recorded on the forefoot to be higher than those recorded on the heel; for the jungle boot, the opposite was the case on a number of surface/treatment combinations.

In terms of the differences in the frictional characteristics of the various types of footwear, a significant main effect of footwear was obtained in all of the ANOVAs. The HSD post-hoc tests showed that the relationships among the means for the eight footwear types varied across analyses. There were no indications in the data that any one type was vastly superior or vastly inferior to the others on all surfaces or all surface treatments. There were surfaces on which the forefoot section of a particular footwear item had relatively high COFs and the heel section had relatively low COFs, or vice versa. For example, on grass, the forepart of the Red Wing achieved some of the highest scores and the heel some of the lowest (Tables A-19 through A-22).

With regard to the military boots, their COFs tended to be among the lowest on the dry surfaces and among the highest on the wet, oily, and greasy surfaces. An exception to this was the grass, where the combat boot yielded relatively low scores on wet, oily, and greasy, as well as on dry, surfaces.

Testing of Footwear Worn Outside the Laboratory

The journals kept by the eight men and the eight women who wore the footwear samples indicated that the activities performed in the footwear included walking indoors and outside, sitting, and standing. The number of hours of wear to which the footwear was exposed ranged from 317 hours to 364 hours, with a mean of 336 hours (S.D. = 16). Walking indoors and out accounted for over 50% of the time spent in the footwear.

Each pair of footwear was weighed prior to the initiation of the wear period and at the end of the period. Only two of the types showed any change in mass, the combat boot and the Red Wing. Both reflected a gain of 0.5 kg per pair. The findings from the materials tests performed on the footwear used outside the laboratory follow.

Impact Test

Impact test data for the forefoot and the heel portions of the worn footwear are presented in Tables B-1 and B-2, respectively. A visual comparison of the forefoot data for the worn (Table B-1) and for the unworn (Table A-1) footwear did not reveal a consistent increase or decrease in the means for the worn items relative to those for the unworn, with the exception of the coefficient of restitution and the energy return values for the forefoot. On these parameters, the values for the worn items were somewhat lower or essentially equal to those for the unworn. For the heel impact data as well, there were few consistencies in the directional changes as a function of wear (Tables A-2 and B-2). However, there was a trend toward increasing times to peak g and increasing maximum pressures with wear.

All ANOVAs performed to compare the impact properties of the various types of worn footwear yielded significant main effects of footwear. As was the case for the impact test results of the unworn items, the eight types of worn footwear can be divided into three groups on the basis of findings for the impact variables as measured at the forefoot and the heel. Again, compared with the other types, the combat and the jungle boots had high peak g readings, short times to peak g, low maximum penetrations, high peak pressures, low coefficients of restitution, and low energy return values. Also, compared with the other types, the Nike Air Max and the Nike cross trainer again had low peak g readings, long times to peak g, high maximum penetrations, low peak pressures, high coefficients of restitution, and high energy return values. For the heel impact measures, the Reebok Pump also had relatively low means for peak g and peak pressure and high means for the remaining four parameters.

The post-hoc procedures performed on the forefoot and the heel impact data for the worn items revealed that the means for the combat and the jungle boot were generally significantly different than the means for the commercial items. In addition, the most favorable scores, those for the Nike cross trainer, were in most instances significantly different from the means for all other footwear types.

With regard to the relationship between the combat and the jungle boots, the means for these two items differed significantly on all forefoot measures except energy return. Unlike the findings for the unworn footwear, the mean peak g measured at the forefoot was higher for the jungle than for the combat boot. For the heel impact measures, the means of the two military boots differed significantly only for maximum penetration, coefficient of restitution, and energy return. The combat boot had the lower mean on each of these measures.

Flexibility Test

The flexibility data for the worn footwear are presented in Table B-3. Comparison of these data with the data collected on the unworn items (Table A-3) revealed some consistencies in the relationships between the two data sets. For example, regardless of the presence or absence of the upper, the Nike Air Max and the Red Wing were at least as flexible when tested in a worn vs. an unworn state, whereas the Reebok Pump was stiffer. For the military boots, the findings differed depending upon whether the data were acquired with the upper in place or removed. In the absence of the upper, the combat boot was more flexible and the jungle boot less so in the worn compared with the unworn state. With the upper in place, the opposite relationship applied: the combat boot was stiffer and the jungle boot was more flexible when tested in a worn state than when tested in an unworn state.

With regard to the relationships among the footwear types after wear, each ANOVA yielded a significant main effect of footwear (Table B-3). For the data collected with the upper removed, the post-hoc tests revealed that the highest stiffness means, those for the Red Wing, were significantly different than the means for all other footwear types. The combat boot, followed by the Nike Air Max, had the lowest stiffness means. The means for these items were significantly different from the means for all other footwear types. The values for the jungle boot did not fall at either extreme. With the upper in place, the Red Wing again had stiffness values that were significantly higher than those for the other types of footwear, and the Nike Air Max had values that were significantly lower than those for all other footwear. The data for the combat boot and the jungle boot reflected relatively high stiffness values.

Stability Test

The results of the stability testing performed on the medial and the lateral borders of the worn footwear are presented in Table B-4. As was found for the unworn footwear (Table A-4), the stability values for the medial border were generally higher than those for the lateral. The opposite was found only for the Reebok Pump and the Rockport hiking boot.

Comparison of the data on the worn and the unworn items did not indicate any consistent relationships between the two data sets across all footwear types for either the medial or the lateral border. However, for some of the footwear types, specifically the combat boot, the jungle boot, and the Reebok Pump, the stability values for the worn items were higher than those for the unworn; the opposite was the case for the remaining types of footwear.

With regard to the relative stability of the various types of worn footwear tested, the ANOVAs performed on the data from the medial and the lateral borders both yielded significant main effects of footwear (Table B-4). As was the case for the unworn footwear, the combat boot had the highest mean value on the medial border. The HSD post-hoc tests showed that the mean for the combat boot was significantly different than the mean for all other footwear types. The jungle boot had the next highest stability mean; it was significantly higher than all others except the mean for the combat boot. In order of decreasing stability values for the medial border, the jungle boot was followed by the Red Wing. Again as was found for the unworn footwear, the Reebok Pump and the Rockport walking shoe had the lowest stability values. The post-hoc tests showed that the means for these two footwear types were not significantly different from each other, but did differ significantly from the means for the remaining footwear types.

With regard to the stability data for the lateral border, the combat boot, which had the highest value when tested unworn, had the highest value of all the worn items as well. The post-hoc tests showed the mean for the combat boot to be significantly higher than the means for all other footwear. The mean for the jungle boot was significantly higher than that for all items except the combat boot, and the Red Wing was next in descending order. The Rockport walking shoe had the lowest stability value. The post-hoc tests showed that its mean was significantly different than the means for all other items except the Nike Air Max.

Sole Wear Test

The sole wear data for the worn footwear are presented in Table B-5. Compared with the findings from the testing of previously unworn items, after use some of the footwear types took longer to reach the criterion penetration, others took the same number of time periods, and one, specifically the Nike Air Max, took less time (Tables A-5 and B-5).

The ANOVA carried out on the sole wear data of the worn items yielded a significant main effect of footwear. The Tukey HSD procedure revealed that the Nike Air Max, the shoe with the highest mean among the previously unworn items, again took significantly longer to reach the criterion level of wear than the other footwear types did. The Reebok Pump had the next highest values as it did in the testing of the unworn items.

The lowest means were again those for the combat boot, the Red Wing, and the Rockport walking shoe. The post-hoc tests showed that the values for the combat boot and the Red Wing did not differ significantly, but that the mean for the Rockport walking shoe, which was the lowest of all means, was significantly different than the means for all other footwear types.

Water Penetration Test

The findings from the water penetration test performed on the worn footwear are presented in Table B-6. In terms of time to penetration among the footwear types with all-leather uppers, the Nike cross trainer and the Rockport walking shoe did not perform as well in the worn as in the unworn state. The rest of the all-leather footwear did, completing the immersion period without water leakage into the interior (Tables A-6 and B-6).

A significant main effect of footwear was obtained on the ANOVA. The post-hoc tests revealed that the combat boot, the Red Wing, the Reebok Pump, and the Rockport hiking shoe, all-leather items that completed the immersion without signs of leakage, had significantly higher scores than the other footwear types. As was found in the testing of the unworn footwear, the lowest means were associated with the jungle boot and the Nike Air Max, the items that had cloth in the uppers. The means for these two footwear types were found to be significantly lower than those for all other items.

Friction Test

The results of the friction testing of the worn footwear under the 20 combinations of surfaces and surface treatments are presented in Tables B-7 through B-26. Comparison of the forefoot data for the worn and the unworn footwear did not reveal a consistent relationship between the data sets for either the static or the dynamic COFs (Tables A-7 through A-26 and B-7 through B-26). Depending upon the surface/treatment combination, some COFs were higher for the worn than the unworn footwear, others were lower, and others were approximately equal. The same situation was found for the heel data.

As was the case for the unworn footwear, the static and the dynamic COFs for the worn items generally were 0.29 or higher except on the cement and tile surfaces treated with oil or with grease (Tables B-17, B-18, B-25, and B-26). With these surface/treatment combinations, the worn footwear yielded COFs as low as 0.08 and 0.10.

With regard to the frictional characteristics of the various types of worn footwear, each ANOVA yielded a significant main effect of footwear. However, no one footwear type was vastly superior or vastly inferior to the others on all surfaces or all surface treatments (Tables B-7 through B-26). As was the case with the data for the unworn footwear, the COFs of the military boots were among the lowest on dry surfaces and among the highest on wet, oily, and greasy surfaces.

Discussion

The military boots included in this study were developed to meet many requirements. In addition to the goals of enhancing the mobility of the wearer and minimizing the occurrence of lower extremity injury during performance of a wide variety of activities on a wide range of surfaces and terrains, cost, storage life, and a myriad other factors influenced the decisions that led to the versions of the combat and the jungle boots used in this study. The decisions included trade-offs, where some factors were sacrificed for others. No doubt, it can also be said that the design of the commercial items tested emanated from consideration of many factors in addition to the performance efficiency and lower extremity health of the wearer, although the factors may have been different from those influencing military boot development. It is likely that these decisions also included trade-offs in arriving at the finished item. Thus, as is the case for the military footwear, the commercial items do not represent the "ideal" footwear. Furthermore, the commercial footwear items are not appropriate for use as military field boots. However, in the context of the materials testing carried out in the present study, the commercial items are "models" against which to assess the material characteristics of the military boots.

A characteristic of particular concern in military boot development is resistance of the footwear to water penetration. During field operations, military personnel must often pass through bodies of fresh and salt water and transit muddy and swampy areas. There may be no opportunity to replace wet socks and boots with dry ones and, therefore, there is a risk of exposure injuries (Oakley, 1984; Orr and Fainer, 1952). The testing carried out in this study indicated that the combat boot resisted the intrusion of water very well. This was the case whether the item was tested in an unworn state or after having been worn outside the laboratory for a period of time. The other footwear items with all-leather uppers also performed well. On the other hand, water entered the jungle boot quickly, because of the screened eyelets set in the leather portion of the boot upper. However, the jungle boot, as the name implies, was developed for use in hot and wet environments where a major concern is permeability to water vapor, rather than resistance to moisture penetration.

Another concern in military boot development is the frictional characteristics of the outsole. The boots must provide good traction while the wearer is performing various physical activities on a variety of surfaces and terrains. In this study, it was found that all the footwear items had static and dynamic COFs of at least 0.29, except on cement and tile surfaces treated with oil or with grease. This was the case whether the footwear was tested in an unworn state or after it had been worn for a time outside the laboratory. Given that a COF of 0.30 has been cited by some researchers as being the minimum acceptable to avoid slipping (Cavanagh and Williams, 1981; Perkins and Wilson, 1983), it can be said that the footwear items tested, including the military boots, had acceptable frictional characteristics on most surfaces. Also, relative to the commercial items, the combat boot and the jungle boot generally did not have particularly high or low COFs.

As was mentioned with regard to the water penetration and the friction tests, there was little difference on these measures between unworn footwear and footwear that had been worn outside the laboratory. No extreme differences were found between the worn and the unworn items on any of the materials tests carried out in this study. The use outside the laboratory was for a period of eight weeks; the actual hours of wear of the items ranged from 317 hours to 364 hours. According to the journals kept by the men and the women who used the footwear, walking, both inside and outside, accounted for over 50% of the wear time. Failure to find extensive differences between the unworn and the worn footwear on the materials tests may indicate that the items were robust to the effects of wear. On the other hand, it is likely that the number of hours of wear and the exposure of the footwear to the elements and sweat would have been more extensive if the wear phase had been carried out by military personnel engaged in field operations.

The parameters that revealed the greatest differences between the military and the commercial footwear, whether the items were tested in an unworn state or after a period of wear outside the laboratory, were those measured on the impact test. The findings for the combat boot and the jungle boot on the impact test were, however, highly similar, in spite of the fact that the jungle boot has a steel plate set in the outsole that extends the entire length of the boot and the combat boot does not. The Nike Air Max and the Nike cross trainer, commercial shoes designed to attenuate the shocks at impact of the foot with the ground, reduced the peak g and the peak pressure by approximately 50% compared with the military boots. With the Air Max and the cross trainer, peak g and peak pressure were also reduced by some 30% to 40% compared with the Red Wing, a commercial work boot that, of the commercial footwear tested here, had impact characteristics most similar to those of the military boots. Furthermore, shorter times to peak g, indicating a greater jolt to the body upon impact, were obtained with the military boots and the Red Wing than with the Air Max and the cross trainer. Therefore, in terms of the human/footwear system, greater impact forces experienced over a shorter time period are to be expected when the combat boot, the jungle boot, or the Red Wing are being worn compared with the situation when the Air Max or the cross trainer are being used.

In prospective studies of the nature and the frequency of lower extremity disorders occurring among male and female military trainees, Bensel (1976) and Bensel and Kish (1983) found relatively high incidences of stress reactions of the calcaneus and the metatarsals. They hypothesized that the prevalence of the stress reactions was attributable to a lack of impact protection in the trainees' footwear, the combat and the jungle boots. The results of the present study support the hypothesis, at least to the extent that the impact test showed superior shock attenuation properties with some commercial running shoes compared to the military boots.

The impact testing in this study was carried out on both the forefoot and the heel of each footwear item. The impact properties of the heel tended to be superior to those of the forefoot, most likely because of greater thicknesses of material in the heel than in the forefoot. This may not be a concern in footwear used exclusively for running or walking, locomotor activities in which, for most people, the rear part of the shoe strikes the ground before the forepart (Cavanagh, 1980), However, it is a concern in military footwear because of the wide variety of locomotor activities performed in the footwear.

Whether tested in an unworn or a worn condition, the Nike cross trainer had particularly high values for coefficient of restitution and energy return, two more parameters of the impact test, compared with the values for the military boots. In the context of the human/footwear system, more energy would be lost upon ground impact and, thus, more internal energy would be required to propel the body forward with the military boots than with the cross trainer.

A second consideration related to energy expenditure is the weight of footwear. A number of research studies have found that there is a 0.7% to 1.0% increase in the energy cost of locomotion for each 100-g increase in the weight of the footwear, per pair, being worn (Jones, Toner, Daniels, and Knapik, 1984; Jones, Knapik, Daniels, and Toner, 1986; Martin, 1984). The military boots were the heaviest footwear items of all those tested in the present study, and the combat boots increased in weight over the wear period.

The flexibility test performed in this study raises a third issue related to energy expenditure. In the context of the human/footwear system, the less flexible the footwear, the more force the human must apply to bend the shoe, propelling the body into the next step. When tested with the upper in place, the military boots were among the least flexible of the footwear items. This was the case whether the footwear was tested in an unworn or in a worn state. The stiffest of the items tested was the Red Wing work boot, which required more than double the amount of force to bend than the most flexible shoe, the Nike Air Max. The military boots were between the extremes defined by the Red Wing and the Air Max.

Military personnel are exposed to physically strenuous regimens, particularly in combat. Like civilian athletes, they must spend their energy efficiently. The results of the present study suggest that, because of the low energy return, weight, and stiffness of the military footwear, these boots may accelerate energy loss, and the accompanying onset of muscle fatigue, relative to some commercial sports footwear items. The lack of flexibility in the combat and the jungle boots may also stress the plantar aspects of the feet. In their prospective studies of the lower extremity disorders occurring among military trainees, Bensel (1976) and Bensel and Kish (1983) found metatarsalgia, plantar fascitis, and arch pain to be relatively common. It is possible that these problems are attributable to some extent to the stiffness of the military boots.

The results of the sole wear test conducted in this study, in which the rear border of the heel was exposed to an abrading surface, indicate that there are other implications associated with footwear flexibility. The Nike Air Max and the Reebok Pump were low in stiffness as measured on the flexibility test and also took longer to reach the criterion level on the sole wear test than the other footwear types. On the other hand, the Red Wing work boot and the combat boot, which were relatively high in stiffness, wore down relatively quickly.

The Nike Air Max and the Nike cross trainer, shoes with good impact and flexibility characteristics, had among the lowest scores on the stability test. On the other hand, the combat boots and the jungle boots, along with the Red Wing work boots, had the highest scores for stability at both the medial and lateral borders. This was found regardless of whether the footwear was tested in a worn or in an unworn state.

Cavanagh (1980) used the stability test as a measure of rearfoot control, with higher scores indicating better control and, thus, less subtalar joint pronation. Excessive pronation during the support phase of running has been linked to overuse injuries of the hip, knee, Achilles tendon, and foot (Clarke et al., 1984). The superiority of some of the commercial items in the realm of impact cushioning and their relatively low scores in terms of stability illustrate dramatically the conflict between two primary needs in a footwear item, protection of the body against impact shock and stability of the foot to avoid overpronation (Frederick et al., 1984; James, Bates, and Osternig, 1978). Research into design and material configurations has indicated that the conflicting demands may be met in one footwear item if the midsole is relatively thick and firm and the rearfoot is relatively wide at the outsole (Clarke et al., 1984; Frederick et al., 1984).

The findings from this study regarding the differences in shock absorbing properties between such commercial shoes as the Nike Air Max and cross trainer and the military boots suggest changes that may improve the impact characteristics of the boots. Using the commercial shoes as models, it would seem that the boots would benefit from the addition of a pliant, multidensity midsole. A flexible midsole, and the addition to the outsole of flex grooves, such as those found on the forefoot portion of the Nike cross trainer, could also reduce the forefoot stiffness of the military boots.

The extensive requirements that military boots are expected to fulfill, many of which are not germane to footwear for civilian use, must be considered in implementing these modifications in order to avoid compromising the functioning of the boots in field environments. In addition, the suggested changes are based solely on materials testing. More definitive information must await the conclusion of Phase II of this research effort. This is the study now underway to analyze the functioning of individuals wearing the same types of military boots and four of the commercial footwear types used in the materials testing.

Conclusions

This report contains the findings from the first phase of a two-phase research program to gather information about the biomechanical properties of current military boots. In this phase, the combat and the jungle boots were subjected to materials testing, along with six types of commercial sport and work shoes. The next phase is an analysis of the functioning of individuals wearing the same types of military boots and four of the commercial footwear items used in this testing. The long-term objective of the research is to develop, from the data acquired, a series of recommendations for future military footwear with regard to design, materials, or any other features that would benefit the performance and the lower extremity health of military personnel. The commercial items selected for analysis were not developed to meet the extensive requirements that military field boots must fulfill. However, the commercial footwear incorporates material and design concepts that could be adapted to a military boot should this be recommended on the basis of the results of this research program.

The major findings from this study, as they relate to the performance of the military boots on each of the materials tests, are summarized below. The findings apply to the footwear when tested in an unworn state and when tested after a period of wear outside the laboratory.

1. Impact test. Compared with the commercial items, the combat boot and the jungle boot had higher peak g readings, shorter times to peak g, higher peak pressures, lower coefficients of restitution, and lower energy return values.

2. Flexibility test. With the upper in place, the combat and the jungle boots were less flexible than all but one of the commercial items. That item was a leather work boot.

3. Stability test. The military boots and the leather work boot had the highest scores on this test, indicating high medial and lateral stability.

4. Sole wear test. The outsoles of the combat boot, the jungle boot and several of the commercial items were similar in resistance to abrasion on the accelerated wear test. The two footwear types that took longest to reach the criterion level of wear were commercial items that, on the flexibility tests, were found to be the least stiff of all footwear included in this study.

5. Water penetration test. The interior of the combat boot remained dry during the 15 min of water immersion. The interior of the jungle boot did not; water entered the boot through the eyelets set in the arch area. When the boot was tested with the eyelets plugged, the interior also remained dry throughout the 15-min immersion period.

6. Friction test. With the exception of a few surfaces and surface treatments, the static and the dynamic coefficients of friction obtained for the military boots and for the commercial footwear items were at least 0.29, the minimum to avoid slipping. With all footwear types, lower coefficients were obtained on cement and tile surfaces treated with oil or with grease.

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Appendix A

Tables A-1 to A-26: Unworn Footwear Data

Table A-1. Summary Statistics ($\underline{N}$=8) and Results of Statistical Analyses for Impact Test Performed on Forefoot of Unworn Footwear

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
				Footwear					
			Peak g (multiples of acceleration due to gravity)						
$\underline{M}$	33.30	28.52	16.28	14.99	22.76	25.33	24.79	19.34	42.9**
$\underline{S.D.}$	2.26	3.97	1.45	1.43	1.74	1.96	2.70	1.49	
$\underline{HSD}^a$		A	D,E	E	B,C	A,B	A,B	C,D	
				Time to Peak g (ms)					
$\underline{M}$	6.74	7.25	11.44	11.08	7.99	9.32	9.42	10.21	15.9**
$\underline{S.D.}$	1.67	1.20	1.10	1.73	1.66	0.67	1.95	0.36	
$\underline{HSD}^a$	A	A	B	B	A,C	A,B,C	A,B,C	B,C	
				Maximum Penetration (%)					
$\underline{M}$	11.40	11.17	47.22	43.95	21.94	47.26	28.27	24.78	19.6**
$\underline{S.D.}$	3.57	3.80	3.40	4.78	4.58	3.65	5.87	4.73	
$\underline{HSD}^a$	A	A	C	C	B	C	B	B	
				Peak Pressure (N/cm²)					
$\underline{M}$	1560.0	1340.0	762.8	702.1	1068.2	1171.3	1151.2	925.7	33.4**
$\underline{S.D.}$	105.2	129.8	24.9	22.2	113.4	90.8	116.6	17.2	
$\underline{HSD}^a$	A	A,B	C	C	D,E	B,D	B,D	C,E	

Table A-1. Continued.

Statistic	Footwear Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
				Coefficient of Restitution (dimensionless)					
M	0.58	0.54	0.59	0.67	0.61	0.58	0.64	0.63	2.7*
S.D.	0.07	0.09	0.04	0.02	0.07	0.05	0.03	0.04	
HSD[a]	A	A	A	B	B	A	B	B	
				Energy Return (%)					
M	58.4	54.8	59.2	67.5	61.2	58.8	64.5	62.7	2.6*
S.D.	6.7	8.8	3.5	2.6	6.8	5.2	3.2	4.4	
HSD[a]	A,B	A	A,B	C	B,C	A,B	C	C	

[a]Means with the same letter were not significantly different ($p>.05$) on the Tukey HSD test.
*$p<.05$ on $df=7,56$. **$p<.001$ on $df=7,56$.

Table A-2. Summary Statistics (*N*=8) and Results of Statistical Analyses for Impact Test Performed on Heel of Unworn Footwear

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
				Footwear					
			Peak g (multiples of acceleration due to gravity)						
M	29.79	28.39	14.25	11.27	19.72	16.16	15.76	16.67	152.2*
S.D.	1.21	0.68	0.98	0.32	2.63	0.82	1.53	0.35	
HSD[a]	A	A	B			B	B	B	
			Time to Peak g (ms)						
M	5.50	8.21	11.99	13.17	7.94	12.36	10.71	9.03	12.3*
S.D.	1.19	1.77	1.16	1.98	3.02	2.72	1.81	1.17	
HSD[a]	A	A	B		A	B	B	A,B	
			Maximum Penetration (%)						
M	11.41	13.35	28.07	33.96	18.99	26.32	20.88	19.07	34.8*
S.D.	0.64	2.04	4.98	3.11	3.75	2.42	1.13	2.34	
HSD[a]	A	A	B	B	C	B,C	C	C	
			Peak Pressure (N/cm^2)						
M	1396.0	1330.2	668.1	528.0	936.3	758.1	757.6	781.4	121.5*
S.D.	76.3	50.4	54.6	22.2	107.4	58.8	60.6	38.2	
HSD[a]	A	A	B			B	B	B	

Table A-2. Continued.

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
				Footwear					
				Coefficient of Restitution (dimensionless)					
M	0.41	0.46	0.61	0.73	0.54	0.54	0.54	0.58	111.1*
S.D.	0.01	0.02	0.02	0.02	0.04	0.03	0.02	0.08	
HSD[a]	A	A			B	B	B	B	
				Energy Return (%)					
M	41.2	46.0	60.8	73.0	54.0	54.2	53.6	58.2	99.7*
S.D.	0.7	2.2	3.1	2.5	3.7	2.7	2.0	0.8	
HSD[a]	A	A			B	B	B	B	

[a] Means with the same letter were not significantly different ($p > .05$) on the Tukey HSD test.
* $p < .001$ on $df = 7,56$.

Table A-3. Summary Statistics (N=8) and Results of Statistical Analyses for Stiffness (in N/degree) of Unworn Footwear as Measured on the Flexibility Test

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				After 50 Flexes					
No Upper									
M	1.10	1.10	0.97	1.17	2.09	0.98	1.36	1.05	37.5*
S.D.	0.13	0.05	0.13	0.08	0.15	0.11	0.20	0.15	
HSD[a]	A,B	A,B	A	A,B		A	B	A	
With Upper									
M	1.76	2.49	1.35	1.73	3.51	1.39	2.06	1.54	38.5*
S.D.	0.31	0.27	0.16	0.20	0.42	0.19	1.02	0.27	
HSD[a]	A,B	C	B	A,B		B	A,C	A,B	
				After 2095 Flexes					
No Upper									
M	0.97	0.87	0.67	0.93	1.55	0.84	1.17	0.99	28.8*
S.D.	0.12	0.03	0.14	0.05	0.04	0.08	0.16	0.08	
HSD[a]	A,B	A		A		A	B	A,B	
With Upper									
M	1.96	2.16	1.06	1.44	2.58	1.47	1.54	1.83	27.0*
S.D.	0.35	0.28	0.08	0.07	0.17	0.17	0.04	0.21	
HSD[a]	A	A		B		B	B	A	

Table A-3. Continued.

Statistic	Combat Boot	Jungle Boot	Nike Air	Footwear Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
				10 min After Previous Flex					
No Upper									
M	0.95	0.81	0.91	1.01	1.62	0.85	1.18	0.92	29.4*
S.D.	0.16	0.06	0.15	0.09	0.04	0.08	0.16	0.14	
HSD[a]	A,B	A	A	A,B		A	B	A	
With Upper									
M	2.13	2.17	1.10	1.50	2.75	1.11	1.58	1.90	24.0*
S.D.	0.45	0.31	0.12	0.09	0.21	0.05	0.06	0.30	
HSD[a]	A	A	B	C		B	C	A	

[a]Means with the same letter were not significantly different ($p > .05$) on the Tukey HSD test.
*$p < .001$ on $df = 7,56$.

Table A-4. Summary Statistics (*N*=8) and Results of Statistical Analyses for Stability (in N/degree) of Medial and Lateral Borders of Unworn Footwear as Measured on the Stability Test

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
				Medial Border					
M	6.31	5.25	3.12	3.23	4.81	1.97	4.06	2.31	21.3*
S.D.	1.34	0.71	0.34	0.31	0.73	0.54	0.91	0.26	
HSD[a]	A	A,B	C,D	C,D	B	D	B,C	D	
				Lateral Border					
M	5.84	4.47	2.99	2.80	5.04	1.79	3.44	2.11	52.3*
S.D.	0.54	0.76	0.23	0.64	0.57	0.31	0.87	0.46	
HSD[a]	A	B	C,D	C,D	A,B	E	C	D,E	

[a]Means with the same letter were not significantly different ($p>.05$) on the Tukey *HSD* test.
*$p<.001$ on $df=7,56$.

Table A-5. Summary Statistics ($\underline{N}$=8) and Results of Statistical Analyses for Total Time (in s) Required to Penetrate Outsoles of Unworn Footwear to a Depth of 1.9 cm on the Sole Wear Test

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
$\underline{M}$	15	30	90	45	15	75	45	15	4098.2*
$\underline{S.D.}$	0.03	0.02	0.01	0.04	0.05	0.01	0.02	0.01	
$\underline{HSD}$[a]	A			B	A		B	A	

[a]Means with the same letter were not significantly different ($\underline{p}$>.05) on the Tukey $\underline{HSD}$ test.
*$\underline{p}$<.001 on $\underline{df}$=7,56.

Table A-6. Summary Statistics ($\underline{N}$=8) and Results of Statistical Analyses for Time (in min) to Detection of Moisture in the Interior of Unworn Footwear as Measured on the Water Penetration Test

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
$\underline{M}$	15.03	0.49	3.05	15.13	15.23	15.10	15.20	15.22	6104.2*
$\underline{S.D.}$	0.13	0.04	0.20	0.20	0.35	0.27	0.26	0.23	
$\underline{HSD}$[a]	A			A	A	A	A	A	

[a]Means with the same letter were not significantly different ($\underline{p}$>.05) on the Tukey $\underline{HSD}$ test.
*$\underline{p}$<.001 on $\underline{df}$=7,56.

Table A-7. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Dry Asphalt

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.86	1.08	0.95	0.86	1.30	0.81	1.06	0.89	98.3^{*}
$S.D.$	0.03	0.08	0.03	0.03	0.08	0.01	0.04	0.06	
HSD[a]	A,B	D	C	A,B		A	D	B,C	
Heel									
M	0.71	1.07	1.04	0.85	1.09	0.79	1.01	0.89	52.2^{*}
$S.D.$	0.05	0.07	0.07	0.03	0.01	0.01	0.05	0.06	
HSD[a]	A	B	B	C,D	B	A,D	B	C	
					Dynamic				
Forefoot									
M	0.80	0.81	0.84	0.78	0.93	0.74	0.88	0.73	42.3^{*}
$S.D.$	0.04	0.04	0.03	0.01	0.05	0.02	0.03	0.04	
HSD[a]	A,B	A,B	A,C	B,D		D	C	D	
Heel									
M	0.64	0.88	0.89	0.75	0.87	0.74	0.82	0.73	59.2^{*}
$S.D.$	0.06	0.05	0.02	0.02	0.03	0.01	0.03	0.04	
HSD[a]		A	A	B	A,C	B	C	B	

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,56.

Table A-8. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Wet Asphalt

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.93	0.85	0.86	0.75	1.11	0.74	0.88	0.79	47.7*
$S.D.$	0.03	0.12	0.02	0.04	0.05	0.03	0.05	0.03	
HSD[a]	A	B,C	A,B,C	D		D	A,B	C,D	
Heel									
M	0.90	1.07	0.92	0.76	1.03	0.75	0.86	0.79	105.7*
$S.D.$	0.04	0.05	0.03	0.02	0.03	0.02	0.05	0.03	
HSD[a]	A,B	C	B	D	C	D	A	D	
Dynamic									
Forefoot									
M	0.86	0.70	0.76	0.66	0.88	0.65	0.73	0.66	57.2*
$S.D.$	0.02	0.09	0.02	0.02	0.03	0.02	0.10	0.04	
HSD[a]	A	B		B	A	B	B	B	
Heel									
M	0.73	0.90	0.78	0.67	0.89	0.66	0.67	0.66	112.5*
$S.D.$	0.04	0.04	0.01	0.02	0.03	0.02	0.02	0.04	
HSD[a]		A		B	A	B	B	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-9. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Oily" Asphalt

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.70	0.79	0.53	0.43	0.72	0.46	0.60	0.55	80.2*
S.D.	0.04	0.10	0.04	0.03	0.03	0.04	0.02	0.02	
HSD[a]	A		B	C	A	C	D	B,D	
Heel									
M	0.87	0.80	0.54	0.45	0.61	0.49	0.50	0.55	112.3*
S.D.	0.07	0.05	0.07	0.03	0.04	0.03	0.03	0.02	
HSD[a]			A,B	C	D	A,C	A,B,C	B,D	
Dynamic									
Forefoot									
M	0.53	0.59	0.42	0.34	0.48	0.34	0.38	0.38	117.2*
S.D.	0.02	0.06	0.01	0.01	0.03	0.07	0.02	0.02	
HSD[a]	A	A	B	C	B	C	C	C	
Heel									
M	0.50	0.61	0.43	0.32	0.50	0.34	0.38	0.37	84.4*
S.D.	0.03	0.03	0.08	0.02	0.03	0.07	0.02	0.09	
HSD[a]	A			B	A	B,C	C	B,C	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-10. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Greasy" Asphalt

Statistic	Footwear: Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.74	0.67	0.48	0.41	0.70	0.41	0.51	0.49	97.6*
$S.D.$	0.04	0.07	0.05	0.04	0.03	0.04	0.02	0.04	
HSD[a]	A	B	C	D	A,B	D	C	C	
Heel									
M	0.78	0.75	0.54	0.41	0.54	0.44	0.47	0.49	150.5*
$S.D.$	0.04	0.07	0.05	0.04	0.03	0.07	0.04	0.02	
HSD[a]	A	A	B	C	B	C,D	D,E	E	
Dynamic									
Forefoot									
M	0.44	0.47	0.34	0.27	0.50	0.30	0.34	0.37	122.4*
$S.D.$	0.03	0.04	0.02	0.01	0.02	0.02	0.02	0.02	
HSD[a]	A	A,B	C	D	B	D	C	C	
Heel									
M	0.51	0.59	0.40	0.29	0.45	0.31	0.34	0.36	234.5*
$S.D.$	0.02	0.03	0.03	0.01	0.02	0.01	0.01	0.02	
HSD[a]				A		A	B	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-11. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Dry Carpet

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.96	1.11	1.16	0.99	0.99	0.97	1.01	1.00	19.7*
S.D.	0.05	0.09	0.04	0.06	0.02	0.04	0.04	0.03	
HSD[a]	A	B	B	A	A	A	A	A	
Heel									
M	0.78	1.05	1.05	1.01	1.08	0.95	1.05	1.00	40.2*
S.D.	0.02	0.07	0.04	0.04	0.06	0.07	0.02	0.03	
HSD[a]		A,B	A,B	B,C	A	C	A,B	B,C	
Dynamic									
Forefoot									
M	0.82	0.89	1.01	0.86	0.91	0.82	0.89	0.85	37.9*
S.D.	0.03	0.03	0.02	0.05	0.02	0.03	0.02	0.04	
HSD[a]	A	B,C		A,B	C	A	B,C	A,B	
Heel									
M	0.65	0.87	0.85	0.87	0.93	0.70	0.81	0.85	77.9*
S.D.	0.02	0.03	0.01	0.03	0.03	0.07	0.02	0.04	
HSD[a]		A	A,B	A	A		B	A,B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-12. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Wet Carpet

Statistic	Footwear: Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.99	1.22	1.19	1.06	1.42	0.99	1.20	0.77	75.9*
$S.D.$	0.06	0.04	0.06	0.05	0.07	0.03	0.05	0.04	
HSD[a]	A	B	B	A		A	B		
Heel									
M	0.81	1.21	1.15	1.02	1.32	0.96	1.25	0.75	164.5*
$S.D.$	0.03	0.06	0.02	0.06	0.04	0.04	0.03	0.03	
HSD[a]		A,B	A	C		C	B		
Dynamic									
Forefoot									
M	0.86	0.95	0.99	0.90	1.22	0.81	1.03	0.64	106.3*
$S.D.$	0.04	0.03	0.03	0.05	0.04	0.03	0.02	0.03	
HSD[a]	A	B,C	B,D	C		A	D		
Heel									
M	0.71	0.99	0.88	0.85	1.15	0.78	0.90	0.64	154.7*
$S.D.$	0.03	0.02	0.02	0.06	0.05	0.04	0.01	0.03	
HSD[a]			A,B	A			B		

[a]Means with the same letter were not significantly different ($p>.05$) on the Tukey HSD test.
*$p<.001$ on df=7,56.

Table A-13. Summary Statistics (*N*=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Oily" Carpet

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
				Footwear					
				Static					
Forefoot									
M	0.71	0.79	0.67	0.58	0.64	0.55	0.67	0.52	81.2*
S.D.	0.02	0.03	0.06	0.02	0.03	0.05	0.08	0.03	
HSD[a]	A		A,B	C	B	C	A,B	C	
Heel									
M	0.62	0.65	0.51	0.55	0.58	0.67	0.61	0.49	23.1*
S.D.	0.03	0.04	0.02	0.05	0.03	0.07	0.07	0.03	
HSD[a]	A,B,C	A,B	D	D,E	C,E	A	B,C	D	
				Dynamic					
Forefoot									
M	0.50	0.59	0.54	0.50	0.55	0.48	0.52	0.44	206.4*
S.D.	0.02	0.01	0.07	0.07	0.01	0.02	0.02	0.01	
HSD[a]	A		B	A	B		A		
Heel									
M	0.38	0.50	0.44	0.43	0.44	0.56	0.49	0.44	151.2*
S.D.	0.01	0.03	0.06	0.06	0.01	0.01	0.05	0.01	
HSD[a]		A	B	B	B		A	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-14. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Greasy" Carpet

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.78	0.74	0.68	0.57	0.71	0.70	0.54	0.54	72.6*
$S.D.$	0.04	0.03	0.02	0.02	0.03	0.04	0.02	0.05	
HSD[a]	A	A,B	C	D	B,C	B,C	D	D	
Heel									
M	0.62	0.61	0.64	0.53	0.59	0.71	0.61	0.51	39.1*
$S.D.$	0.03	0.03	0.03	0.04	0.02	0.03	0.05	0.02	
HSD[a]	A,B	A,B	A				A,B		
Dynamic									
Forefoot									
M	0.63	0.59	0.57	0.50	0.57	0.60	0.41	0.48	334.6*
$S.D.$	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.03	
HSD[a]		A	A,B		A,B	A	C	C	
Heel									
M	0.53	0.54	0.55	0.44	0.56	0.60	0.42	0.48	163.2*
$S.D.$	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.02	
HSD[a]	A	A,B	A,B	C	B		C	A	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-15. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Dry Cement

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.48	0.50	0.66	0.69	0.58	0.72	0.57	0.55	101.6*
$S.D.$	0.04	0.04	0.01	0.06	0.03	0.04	0.05	0.04	
HSD[a]	A	A	C	C	B	C	B	B	
Heel									
M	0.49	0.52	0.62	0.68	0.55	0.75	0.61	0.55	62.1*
$S.D.$	0.02	0.02	0.03	0.05	0.02	0.03	0.05	0.04	
HSD[a]	A	A	B	B,C	D	C	B	D	
Dynamic									
Forefoot									
M	0.44	0.47	0.60	0.52	0.55	0.63	0.48	0.48	121.3*
$S.D.$	0.02	0.02	0.02	0.03	0.01	0.03	0.01	0.01	
HSD[a]	A	A,B					B	B	
Heel									
M	0.44	0.51	0.61	0.56	0.50	0.68	0.46	0.48	109.3*
$S.D.$	0.03	0.03	0.02	0.03	0.02	0.02	0.01	0.03	
HSD[a]	A	B			B		A,C	B,C	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-16. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Wet Cement

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.62	0.72	0.47	0.54	0.67	0.67	0.75	0.75	74.8*
S.D.	0.01	0.05	0.03	0.02	0.03	0.04	0.02	0.06	
HSD[a]		A,B			A	A	B	B	
Heel									
M	0.68	0.66	0.64	0.66	0.63	0.64	0.75	0.75	15.7*
S.D.	0.02	0.04	0.04	0.03	0.02	0.04	0.02	0.07	
HSD[a]	A	A	A	A	A	A	B	B	
					Dynamic				
Forefoot									
M	0.59	0.66	0.34	0.32	0.57	0.57	0.51	0.60	357.3*
S.D.	0.02	0.02	0.02	0.03	0.02	0.01	0.02	0.02	
HSD[a]	A		B	B	A	A		A	
Heel									
M	0.64	0.57	0.50	0.48	0.58	0.50	0.50	0.60	46.7*
S.D.	0.04	0.02	0.04	0.02	0.02	0.05	0.01	0.02	
HSD[a]	A	B	C	C	B	C	C	A,B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-17. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Oily" Cement

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Footwear				
					Static				
Forefoot									
M	0.39	0.36	0.18	0.17	0.21	0.25	0.28	0.28	176.7*
$S.D.$	0.03	0.03	0.01	0.02	0.03	0.02	0.01	0.01	
HSD[a]			A	A			B	B	
Heel									
M	0.47	0.32	0.27	0.22	0.30	0.22	0.31	0.28	57.8*
$S.D.$	0.05	0.02	0.02	0.05	0.03	0.02	0.02	0.02	
HSD[a]		A	B	C	A,B	C	A,B	A,B	
					Dynamic				
Forefoot									
M	0.21	0.19	0.12	0.10	0.13	0.18	0.17	0.15	117.2*
$S.D.$	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	
HSD[a]	A	A,B	C	C	C	B	B	B	
Heel									
M	0.19	0.26	0.18	0.10	0.12	0.13	0.18	0.14	147.4*
$S.D.$	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	
HSD[a]	A		A	B	B	B	A	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-18. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Greasy" Cement

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.25	0.22	0.14	0.16	0.21	0.26	0.21	0.27	69.1*
$S.D.$	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.01	
HSD[a]	A	B	C	C	B	A	B	A	
Heel									
M	0.27	0.26	0.20	0.21	0.20	0.22	0.16	0.27	53.6*
$S.D.$	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	
HSD[a]	A	A	B	B	B	B		A	
Dynamic									
Forefoot									
M	0.18	0.17	0.11	0.10	0.16	0.18	0.13	0.21	54.3*
$S.D.$	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.01	
HSD[a]	A	A,B	C	C	B	A	C	A	
Heel									
M	0.14	0.20	0.16	0.15	0.19	0.16	0.13	0.21	37.2*
$S.D.$	0.01	0.01	0.01	0.02	0.03	0.01	0.01	0.01	
HSD[a]	A,B	B	A	A	B	A	A	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-19. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Dry Grass

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.48	0.50	0.66	0.69	0.58	0.72	0.56	0.54	275.7*
$S.D.$	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.01	
HSD[a]	A	A			B		B,C	C	
Heel									
M	0.49	0.52	0.63	0.68	0.55	0.75	0.61	0.54	270.3*
$S.D.$	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	
HSD[a]		A	B		C		B	A,C	
					Dynamic				
Forefoot									
M	0.44	0.47	0.50	0.52	0.50	0.63	0.46	0.49	110.2*
$S.D.$	0.02	0.01	0.03	0.02	0.03	0.01	0.01	0.02	
HSD[a]	A	B,C	D,E	D	D,E		A,B	C,E	
Heel									
M	0.44	0.43	0.51	0.56	0.51	0.68	0.48	0.49	215.1*
$S.D.$	0.01	0.02	0.02	0.01	0.03	0.02	0.01	0.01	
HSD[a]	A	A	B		B		C	B,C	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-20. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Wet Grass

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.85	0.95	0.95	0.92	1.18	0.81	1.03	0.88	25.8*
S.D.	0.05	0.01	0.05	0.07	0.08	0.07	0.03	0.04	
HSD[a]	A,B	A,C	A,C	A		B	C	A	
Heel									
M	0.70	1.22	0.71	0.84	0.73	0.95	0.93	0.87	393.6*
S.D.	0.08	0.08	0.05	0.08	0.04	0.05	0.02	0.05	
HSD[a]	A		A		A	B	B		
					Dynamic				
Forefoot									
M	0.68	0.61	0.82	0.78	0.86	0.71	0.71	0.70	81.1*
S.D.	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.02	
HSD[a]	A		B	B		A	A	A	
Heel									
M	0.51	0.88	0.60	0.72	0.60	0.79	0.69	0.71	361.7*
S.D.	0.03	0.05	0.04	0.01	0.04	0.05	0.03	0.05	
HSD[a]			A		A		B	B	

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,56.

Table A-21. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Oily" Grass

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				Footwear					
				Static					
Forefoot									
M	0.75	0.85	0.74	0.72	0.91	0.57	0.85	0.86	32.6*
$S.D.$	0.03	0.10	0.07	0.05	0.08	0.01	0.05	0.03	
HSD[a]	A	B	A	A	B		B	B	
Heel									
M	0.56	1.02	0.66	0.64	0.63	0.67	0.85	0.84	33.2*
$S.D.$	0.07	0.01	0.07	0.01	0.10	0.06	0.11	0.07	
HSD[a]	A		A	A	A	A	B	B	
				Dynamic					
Forefoot									
M	0.53	0.59	0.54	0.57	0.64	0.46	0.55	0.55	26.0*
$S.D.$	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.02	
HSD[a]	A	B	A,B	A,B			A,B	A,B	
Heel									
M	0.41	0.59	0.46	0.53	0.45	0.65	0.55	0.56	11.0*
$S.D.$	0.02	0.06	0.04	0.04	0.02	0.01	0.02	0.04	
HSD[a]	A	B	A	C	A	B	C	C	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-22. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Greasy" Grass

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.76	0.86	0.82	0.86	0.99	0.71	0.86	0.92	51.4*
$S.D.$	0.04	0.04	0.03	0.06	0.06	0.03	0.07	0.02	
HSD[a]	A	B	A,B	B		A	B		
Heel									
M	0.59	0.97	0.71	0.76	0.60	0.76	0.86	0.92	59.4*
$S.D.$	0.06	0.02	0.05	0.04	0.04	0.07	0.01	0.02	
HSD[a]	A	B	C	C	A	C	D	B,D	
Dynamic									
Forefoot									
M	0.72	0.67	0.77	0.81	0.83	0.67	0.67	0.74	36.4*
$S.D.$	0.03	0.05	0.01	0.02	0.04	0.02	0.04	0.02	
HSD[a]	A	A	B	C	C	A	A	A,B	
Heel									
M	0.44	0.78	0.57	0.70	0.45	0.65	0.64	0.78	144.4*
$S.D.$	0.02	0.04	0.05	0.02	0.03	0.02	0.04	0.04	
HSD[a]	A	B			A	C	C	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-23. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Dry Tile

Statistic	Footwear: Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.79	0.57	0.66	0.70	0.67	0.87	0.92	0.93	32.1*
$S.D.$	0.01	0.03	0.03	0.07	0.10	0.07	0.07	0.09	
HSD[a]	A,B	C	C,D	A,D	C,D	B,E	E	E	
Heel									
M	0.64	0.59	0.69	0.75	0.70	0.78	0.62	0.92	21.8*
$S.D.$	0.05	0.09	0.08	0.08	0.07	0.06	0.07	0.03	
HSD[a]	A,B	B	A,C	C	A,C	C	A,B		
Dynamic									
Forefoot									
M	0.68	0.48	0.57	0.59	0.59	0.81	0.84	0.86	45.5*
$S.D.$	0.06	0.04	0.02	0.01	0.09	0.06	0.01	0.08	
HSD[a]	A	B	B,C	A,C	A,C	D	D	D	
Heel									
M	0.53	0.49	0.59	0.66	0.60	0.68	0.48	0.84	26.9*
$S.D.$	0.05	0.09	0.06	0.08	0.05	0.05	0.01	0.07	
HSD[a]	A,B	A	B	C	B	C	A		

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,56.

Table A-24. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on Wet Tile

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Footwear				
					Static				
Forefoot									
M	0.65	0.66	0.57	0.67	0.71	0.72	0.80	0.78	17.0*
$S.D.$	0.08	0.03	0.04	0.03	0.04	0.09	0.04	0.06	
HSD^a	A	A		A	A,B	A,B	C	B,C	
Heel									
M	0.54	0.70	0.65	0.85	0.66	0.76	0.78	0.78	43.8*
$S.D.$	0.04	0.03	0.05	0.05	0.04	0.03	0.02	0.06	
HSD^a		A,B	A		A	B,C	C	C	
					Dynamic				
Forefoot									
M	0.44	0.55	0.34	0.48	0.58	0.51	0.63	0.61	69.4*
$S.D.$	0.02	0.01	0.03	0.02	0.02	0.05	0.04	0.06	
HSD^a	A	B,C		A,D	B,E	C,D	E	E	
Heel									
M	0.43	0.58	0.53	0.60	0.55	0.54	0.49	0.63	26.5*
$S.D.$	0.02	0.05	0.04	0.04	0.03	0.05	0.04	0.03	
HSD^a		A,B,C	D	A,B	A,C,D	C,D	D	B	

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,56.

Table A-25. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Oily" Tile

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.40	0.32	0.15	0.13	0.17	0.21	0.32	0.24	116.2*
S.D.	0.05	0.02	0.01	0.01	0.01	0.02	0.04	0.02	
HSD[a]		A	B,C	B	C	D	A	D	
Heel									
M	0.41	0.24	0.22	0.18	0.30	0.16	0.26	0.24	89.3*
S.D.	0.03	0.03	0.01	0.01	0.04	0.09	0.01	0.02	
HSD[a]		A,B	A	C		C	B	A,B	
					Dynamic				
Forefoot									
M	0.16	0.19	0.11	0.10	0.13	0.16	0.18	0.13	125.2*
S.D.	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	
HSD[a]	A	A	B	B	B	A	A	B	
Heel									
M	0.12	0.17	0.14	0.10	0.11	0.12	0.16	0.13	22.4*
S.D.	0.01	0.03	0.01	0.01	0.01	0.01	0.01	0.01	
HSD[a]	A,B	C	A,D	E	B,E	A,B	C,D	A,B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,56.

Table A-26. Summary Statistics (N=8) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Unworn Footwear on "Greasy" Tile

Statistic	Footwear: Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.25	0.23	0.15	0.17	0.17	0.26	0.21	0.26	40.6*
S.D.	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.03	
HSD[a]	A	A,B	C	C	C	A	B	A	
Heel									
M	0.19	0.17	0.18	0.19	0.19	0.22	0.18	0.26	15.9*
S.D.	0.01	0.04	0.01	0.02	0.01	0.01	0.02	0.03	
HSD[a]	A	A	A	A	A		A		
Dynamic									
Forefoot									
M	0.19	0.16	0.10	0.11	0.14	0.17	0.14	0.21	118.3*
S.D.	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	
HSD[a]		A	B	B	C	A	C		
Heel									
M	0.13	0.14	0.14	0.12	0.17	0.16	0.12	0.21	24.6*
S.D.	0.01	0.05	0.01	0.01	0.02	0.02	0.01	0.01	
HSD[a]	A,B	A,B	A,B	B	C	A,C	B		

[a]Means with the same letter were not significantly different ($p>.05$) on the Tukey HSD test.
*$p<.001$ on $df=7,56$.

Appendix B

Tables B-1 to B-26: Worn Footwear Data

Table B-1. Summary Statistics ($\underline{N}$=4) and Results of Statistical Analyses for Impact Test Performed on Forefoot of Worn Footwear

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
Peak g (multiples of acceleration due to gravity)									
$\underline{M}$	32.06	35.01	17.33	14.51	27.28	21.21	22.51	18.93	377.4*
$\underline{S.D.}$	1.63	0.82	2.47	4.01	2.46	1.64	4.08	1.76	
$\underline{HSD}^a$			A			B	B	A	
Time to Peak g (ms)									
$\underline{M}$	5.80	7.10	9.51	13.52	9.50	10.00	8.71	9.71	109.0*
$\underline{S.D.}$	1.65	2.65	4.08	3.18	3.45	3.76	2.71	2.45	
$\underline{HSD}^a$			A,B		A,B	A	B	A,B	
Maximum Penetration (%)									
$\underline{M}$	15.29	24.02	32.96	40.52	26.09	36.94	22.64	26.22	584.9*
$\underline{S.D.}$	2.26	1.18	7.58	4.09	5.95	1.79	5.59	2.07	
$\underline{HSD}^a$		A			B		A	B	
Peak Pressure (N/cm²)									
$\underline{M}$	1570.4	1732.3	853.0	716.2	1344.5	1119.0	1105.3	933.6	113.5*
$\underline{S.D.}$	46.8	12.7	8.2	8.2	35.9	57.3	81.9	66.0	
$\underline{HSD}^a$			A,B	A		C	C	B	

Table B-1. Continued.

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
	Coefficient of Restitution (dimensionless)								
M	0.50	0.45	0.56	0.68	0.53	0.45	0.51	0.55	25.4*
S.D.	0.02	0.02	0.03	0.03	0.04	0.02	0.02	0.02	
HSD[a]	A	B	A		A	B	A	A	
	Energy Return (%)								
M	50.1	45.3	55.7	68.1	53.3	45.1	51.1	55.0	41.6*
S.D.	1.6	1.7	3.0	3.3	6.8	1.6	1.6	1.5	
HSD[a]	A,B	A	C		B,C	A	B,C	B,C	

[a]Means with the same letter were not significantly different ($p > .05$) on the Tukey *HSD* test.
*$p < .001$ on $df = 7,24$.

Table B-2. Summary Statistics (N=4) and Results of Statistical Analyses for Impact Test Performed on Heel of Worn Footwear

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Footwear				
Peak g (multiples of acceleration due to gravity)									
M	30.84	30.08	15.40	12.76	22.16	14.76	16.75	17.05	626.4*
$S.D.$	6.95	7.76	3.27	6.13	1.25	6.55	5.74	4.12	
HSD^a	A	A	B	B		B	C	C	
Time to Peak g (ms)									
M	8.00	8.63	12.13	15.53	10.84	12.61	11.70	10.13	70.6*
$S.D.$	0.82	0.86	0.11	0.41	0.66	0.49	0.57	0.25	
HSD^a	A	A	B,C		B,D	C	B,C	D	
Maximum Penetration (%)									
M	14.27	17.35	25.51	34.21	18.30	29.93	22.31	18.61	471.8*
$S.D.$	2.13	1.00	4.87	6.41	2.45	7.76	8.17	4.90	
HSD^a		A			A			A	
Peak Pressure (N/cm^2)									
M	1522.3	1473.2	759.3	615.5	1093.4	725.4	826.9	841.6	357.1*
$S.D.$	18.0	51.2	18.7	12.3	77.6	20.4	57.5	16.4	
HSD^a	A	A	B,C			B	C	C	

Table B-2. Continued.

Statistic	Footwear Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
				Coefficient of Restitution (dimensionless)					
M	0.35	0.44	0.62	0.68	0.49	0.56	0.55	0.58	163.7^{*}
S.D.	0.02	0.02	0.04	0.03	0.05	0.01	0.01	0.04	
HSD[a]						A	A	A	
				Energy Return (%)					
M	35.3	44.2	62.1	68.1	49.1	56.0	55.2	58.1	157.9^{*}
S.D.	0.7	0.7	0.6	0.3	0.8	0.5	0.9	0.8	
HSD[a]						A	A	A	

[a]Means with the same letter were not significantly different ($p>.05$) on the Tukey HSD test.
$^{*}p<.001$ on $df=7,24$.

Table B-3. Summary Statistics (*N*=4) and Results of Statistical Analyses for Stiffness (in N/degree) of Worn Footwear as Measured on the Flexibility Test

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
After 50 Flexes									
No Upper									
M	0.86	1.17	0.84	1.10	1.58	1.09	1.25	1.03	366.8*
S.D.	0.12	0.15	0.03	0.14	0.15	0.04	0.14	0.10	
HSD[a]	A		A	B		B			
With Upper									
M	1.83	1.81	0.89	1.73	2.57	1.54	1.71	1.45	151.2*
S.D.	0.03	0.04	0.07	0.09	0.04	0.19	0.29	0.25	
HSD[a]	A	A		A		B,C	A,B	C	
After 2095 Flexes									
No Upper									
M	0.78	1.06	0.89	0.97	1.41	1.08	1.18	1.18	216.7*
S.D.	0.18	0.17	0.10	0.02	0.06	0.05	0.05	0.06	
HSD[a]		A				A	B	B	
With Upper									
M	1.61	1.59	0.84	1.50	2.51	1.34	1.69	1.48	36.3*
S.D.	0.45	0.59	0.10	0.24	0.32	0.16	0.17	0.15	
HSD[a]	A	A		A		A	A	A	

Table B-3. Continued.

Statistic	Combat Boot	Jungle Boot	Nike Air	Footwear Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				10 min After Previous Flex					
No Upper									
M	0.76	1.07	0.84	1.00	1.48	1.16	1.18	1.18	675.7*
S.D.	0.02	0.14	0.12	0.11	0.16	0.05	0.11	0.13	
HSD[a]	A		A			B	B	B	
With Upper									
M	1.58	1.66	0.82	1.56	2.29	1.37	1.63	1.57	535.3*
S.D.	0.20	0.11	0.10	0.10	0.16	0.12	0.10	0.19	
HSD[a]	A,B	A		B			A,B	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,24.

Table B-4. Summary Statistics (N=4) and Results of Statistical Analyses for Stability (in N/degree) of Medial and Lateral Borders of Worn Footwear as Measured on the Stability Test

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				Footwear					
				Medial Border					
M	6.73	5.33	2.71	3.02	4.17	2.25	3.08	2.24	743.9*
$S.D.$	0.34	0.15	0.07	0.08	0.04	0.03	0.16	0.10	
HSD[a]				A		B	A	B	
				Lateral Border					
M	6.16	5.00	2.22	2.46	3.74	2.32	3.55	2.05	146.7*
$S.D.$	0.53	0.14	0.14	0.24	0.19	0.15	0.46	0.47	
HSD[a]			A,B	C		A,C		B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,24.

Table B-5. Summary Statistics ($\underline{N}$=4) and Results of Statistical Analyses for Total Time (in s) Required to Penetrate Outsoles of Worn Footwear to a Depth of 1.9 cm on the Sole Wear Test

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
$\underline{M}$	30	60	76	45	30	90	45	15	322.3*
$\underline{S}.\underline{D}.$	0.10	0.15	0.91	0.81	0.86	0.65	0.85	0.69	
$\underline{HSD}$[a]	A			B	A		B		

[a] Means with the same letter were not significantly different ($\underline{p}>.05$) on the Tukey $\underline{HSD}$ test.
* $\underline{p}<.001$ on $\underline{df}=7,24$.

Table B-6. Summary Statistics (N=4) and Results of Statistical Analyses for Time (in min) to Detection of Moisture in the Interior of Worn Footwear as Measured on the Water Penetration Test

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
M	15.13	0.50	0.50	6.13	15.03	15.17	15.22	10.20	5293.9*
$S.D.$	0.22	0.01	0.17	0.15	0.21	0.21	0.26	0.18	
HSD[a]	A	B	B		A	A	A		

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,24.

Table B-7. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Dry Asphalt

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.48	0.83	0.70	0.67	0.81	0.50	0.68	0.43	43.5*
$S.D.$	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.01	
HSD[a]	A		B	B		A	B	A	
Heel									
M	0.50	0.88	0.70	0.71	0.60	0.69	0.67	0.38	327.5*
$S.D.$	0.02	0.01	0.03	0.02	0.01	0.02	0.02	0.01	
HSD[a]			A	A		A	A		
Dynamic									
Forefoot									
M	0.42	0.70	0.62	0.61	0.73	0.45	0.63	0.37	110.3*
$S.D.$	0.02	0.01	0.05	0.01	0.02	0.01	0.02	0.03	
HSD[a]	A,B		C	C		A	C	B	
Heel									
M	0.41	0.74	0.56	0.67	0.56	0.58	0.67	0.36	85.6*
$S.D.$	0.04	0.01	0.02	0.07	0.02	0.02	0.02	0.03	
HSD[a]	A	B	C	B	C	C	B	A	

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,24.

Table B-8. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Wet Asphalt

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				Static					
Forefoot									
M	0.75	0.86	0.69	0.69	0.66	0.75	0.67	0.74	20.0*
S.D.	0.03	0.10	0.03	0.07	0.08	0.01	0.01	0.01	
HSD[a]	A		A,B	A,B	B	A	B	A	
Heel									
M	0.71	0.76	0.65	0.69	0.71	0.63	0.67	0.74	9.3*
S.D.	0.06	0.04	0.07	0.03	0.05	0.03	0.01	0.02	
HSD[a]	A,B,C	C	A,D	A,B,D	A,B,C	D	A,D	B,C	
				Dynamic					
Forefoot									
M	0.63	0.67	0.57	0.53	0.59	0.61	0.48	0.56	42.0*
S.D.	0.02	0.02	0.02	0.01	0.06	0.03	0.01	0.02	
HSD[a]	A		B,C	C	A,B	A		B,C	
Heel									
M	0.57	0.58	0.51	0.63	0.61	0.53	0.55	0.56	25.0*
S.D.	0.02	0.03	0.03	0.03	0.03	0.03	0.01	0.02	
HSD[a]	A	A,B	C		B	C,D	A,D	A,D	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,24.

Table B-9. Summary Statistics ($\underline{N}$=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Oily" Asphalt

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
					Footwear				
					Static				
Forefoot									
M	0.75	0.80	0.45	0.45	0.58	0.39	0.50	0.55	101.1*
S.D.	0.09	0.06	0.06	0.01	0.02	0.04	0.02	0.01	
HSD[a]	A	A	B,C	B,C	D	B	C	D	
Heel									
M	0.73	0.75	0.50	0.41	0.64	0.43	0.54	0.55	74.1*
S.D.	0.08	0.03	0.02	0.04	0.08	0.04	0.02	0.04	
HSD[a]	A	A	B	C		C	B	B	
					Dynamic				
Forefoot									
M	0.58	0.60	0.39	0.35	0.51	0.31	0.39	0.40	221.4*
S.D.	0.04	0.04	0.01	0.02	0.01	0.02	0.01	0.01	
HSD[a]	A	A	B				B	B	
Heel									
M	0.54	0.60	0.40	0.35	0.51	0.32	0.39	0.40	220.0*
S.D.	0.02	0.04	0.02	0.02	0.02	0.01	0.02	0.02	
HSD[a]			A	B		B	A	A	

[a]Means with the same letter were not significantly different ($\underline{p}$>.05) on the Tukey HSD test.
*$\underline{p}$<.001 on $\underline{df}$=7,24.

Table B-10. Summary Statistics ($\underline{N}$=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Greasy" Asphalt

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
					Static				
Forefoot									
$\underline{M}$	0.69	0.74	0.43	0.47	0.55	0.38	0.47	0.57	87.7*
$\underline{S.D.}$	0.06	0.07	0.03	0.02	0.04	0.02	0.02	0.05	
$\underline{HSD}$[a]	A	A	B,C	B	D	C	B	D	
Heel									
$\underline{M}$	0.70	0.67	0.50	0.39	0.55	0.43	0.57	0.57	51.9*
$\underline{S.D.}$	0.07	0.04	0.05	0.05	0.04	0.04	0.02	0.05	
$\underline{HSD}$[a]	A	A	B,C	D	B,E	C,D	E	E	
					Dynamic				
Forefoot									
$\underline{M}$	0.52	0.55	0.37	0.33	0.44	0.30	0.33	0.38	297.9*
$\underline{S.D.}$	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.02	
$\underline{HSD}$[a]	A	A	B	B,C		C	B,C	B	
Heel									
$\underline{M}$	0.50	0.51	0.35	0.30	0.43	0.31	0.41	0.38	136.1*
$\underline{S.D.}$	0.03	0.04	0.02	0.01	0.02	0.01	0.05	0.02	
$\underline{HSD}$[a]	A	A	B	C	D	C	D	B	

[a]Means with the same letter were not significantly different ($\underline{p}$>.05) on the Tukey $\underline{HSD}$ test.
*$\underline{p}$<.001 on $\underline{df}$=7,24.

Table B-11. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Dry Carpet

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.84	1.10	0.97	1.01	1.07	1.12	1.11	0.91	64.6*
$S.D.$	0.05	0.01	0.03	0.05	0.05	0.05	0.01	0.05	
HSD[a]		A,B	C	C	B	A	A		
Heel									
M	0.63	0.96	1.09	0.90	1.07	1.01	0.97	0.91	76.2*
$S.D.$	0.06	0.02	0.04	0.01	0.09	0.05	0.01	0.03	
HSD[a]		A,B	C	A	C	B,C	A,B	A	
Dynamic									
Forefoot									
M	0.78	0.89	0.89	0.94	0.93	0.98	1.06	0.79	88.0*
$S.D.$	0.01	0.03	0.03	0.08	0.03	0.02	0.01	0.01	
HSD[a]	A	B	B	B	B	B		A	
Heel									
M	0.54	0.89	0.84	0.76	0.89	0.86	0.72	0.79	113.8*
$S.D.$	0.04	0.02	0.04	0.01	0.06	0.07	0.01	0.01	
HSD[a]		A	A	B	A	A	B	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,24.

Table B-12. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Wet Carpet

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Footwear				
Static									
Forefoot									
M	0.77	0.84	0.60	0.63	0.81	0.72	0.77	0.79	105.1*
$S.D.$	0.03	0.05	0.02	0.04	0.04	0.03	0.04	0.04	
HSD[a]	A,B	C	D	D	A,C	B	A,B	A,C	
Heel									
M	0.65	0.64	0.81	0.71	1.06	0.71	0.98	0.77	111.6*
$S.D.$	0.04	0.03	0.04	0.05	0.08	0.03	0.05	0.01	
HSD[a]	A,B	A	C	B,D	E	B,D	E	C,D	
Dynamic									
Forefoot									
M	0.67	0.74	0.47	0.55	0.76	0.61	0.55	0.70	54.8*
$S.D.$	0.09	0.03	0.03	0.02	0.04	0.02	0.01	0.04	
HSD[a]		A		B	A	B	B	A	
Heel									
M	0.55	0.57	0.75	0.68	0.89	0.60	0.60	0.70	79.2*
$S.D.$	0.04	0.01	0.04	0.03	0.07	0.07	0.01	0.02	
HSD[a]	A	A	B	C		A	A	B,C	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,24.

Table B-13. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Oily" Carpet

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				Footwear					
				Static					
Forefoot									
M	0.62	0.71	0.47	0.56	0.62	0.58	0.56	0.61	155.3*
$S.D.$	0.03	0.03	0.02	0.03	0.03	0.02	0.01	0.02	
HSD[a]	A			B	A	B	B	A	
Heel									
M	0.66	0.66	0.60	0.49	0.61	0.56	0.58	0.62	28.4*
$S.D.$	0.05	0.02	0.02	0.02	0.05	0.04	0.01	0.02	
HSD[a]	A	A	B,C		A,B	C	C	A,B	
				Dynamic					
Forefoot									
M	0.48	0.57	0.42	0.46	0.47	0.48	0.45	0.45	90.4*
$S.D.$	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.01	
HSD[a]	A			A,B	A,B	A	B	B	
Heel									
M	0.37	0.55	0.52	0.36	0.46	0.51	0.45	0.45	51.9*
$S.D.$	0.01	0.01	0.02	0.07	0.01	0.02	0.01	0.01	
HSD[a]	A	B	B	A	C	B	C	C	

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,24.

Table B-14. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Greasy" Carpet

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				Static					
Forefoot									
M	0.63	0.77	0.46	0.66	0.62	0.58	0.50	0.65	37.8*
$S.D.$	0.04	0.05	0.02	0.03	0.02	0.02	0.02	0.01	
HSD^a	A,B		C	A	A,B	B	C	A	
Heel									
M	0.60	0.61	0.62	0.51	0.64	0.59	0.54	0.66	31.8*
$S.D.$	0.04	0.03	0.02	0.05	0.03	0.03	0.02	0.01	
HSD^a	A,B	A,B	A,B	C	A	B	C	A	
				Dynamic					
Forefoot									
M	0.52	0.56	0.43	0.54	0.53	0.52	0.40	0.45	178.1*
$S.D.$	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.02	
HSD^a	A			B	A,B	A			
Heel									
M	0.44	0.55	0.55	0.44	0.53	0.57	0.45	0.40	134.2*
$S.D.$	0.02	0.03	0.01	0.02	0.01	0.02	0.01	0.01	
HSD^a	A	B,C	B,C	A	B	C	A	A	

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,24.

Table B-15. Summary Statistics ($\underline{N}$=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Dry Cement

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
					Static				
Forefoot									
M	0.54	0.57	0.65	0.61	0.78	0.92	0.88	0.83	130.2*
S.D.	0.04	0.03	0.03	0.03	0.05	0.05	0.07	0.05	
HSD[a]	A	A,B	C	B,C	D	E	E	D,E	
Heel									
M	0.54	0.60	0.83	0.80	0.61	0.73	0.75	0.83	75.0*
S.D.	0.05	0.02	0.03	0.06	0.04	0.04	0.01	0.06	
HSD[a]		A	B	B	A	C	C	B	
					Dynamic				
Forefoot									
M	0.39	0.48	0.52	0.56	0.60	0.85	0.72	0.70	204.6*
S.D.	0.02	0.02	0.03	0.02	0.03	0.04	0.01	0.05	
HSD[a]		A	A,B	B,C	C		D	D	
Heel									
M	0.42	0.51	0.69	0.66	0.49	0.68	0.64	0.70	114.4*
S.D.	0.02	0.02	0.05	0.03	0.04	0.04	0.01	0.04	
HSD[a]		A	B	B	A	B	B	B	

[a]Means with the same letter were not significantly different ($\underline{p}$>.05) on the Tukey *HSD* test.
*$\underline{p}$<.001 on $\underline{df}$=7,24.

Table B-16. Summary Statistics ($\underline{N}$=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Wet Cement

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
				Footwear					
Static									
Forefoot									
$\underline{M}$	0.66	0.78	0.78	0.76	0.81	0.79	0.48	0.92	75.2*
$\underline{S.D.}$	0.08	0.04	0.04	0.05	0.04	0.04	0.07	0.03	
$\underline{HSD}$[a]		A	A	A	A	A			
Heel									
$\underline{M}$	0.73	0.86	0.49	0.42	1.04	0.69	0.96	0.92	455.5*
$\underline{S.D.}$	0.04	0.03	0.03	0.03	0.04	0.03	0.05	0.03	
$\underline{HSD}$[a]	A	B	C	C		A	B	B	
Dynamic									
Forefoot									
$\underline{M}$	0.55	0.57	0.71	0.68	0.60	0.74	0.26	0.79	140.7*
$\underline{S.D.}$	0.06	0.04	0.07	0.05	0.04	0.05	0.01	0.02	
$\underline{HSD}$[a]	A	A	B	B	A	B		B	
Heel									
$\underline{M}$	0.62	0.65	0.43	0.32	0.84	0.64	0.80	0.79	402.8*
$\underline{S.D.}$	0.04	0.03	0.02	0.03	0.04	0.03	0.05	0.02	
$\underline{HSD}$[a]	A	A			B	A	B	B	

[a]Means with the same letter were not significantly different ($\underline{p}$>.05) on the Tukey $\underline{HSD}$ test.
*$\underline{p}$<.001 on $\underline{df}$=7,24.

Table B-17. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Oily" Cement

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Footwear				
Static									
Forefoot									
M	0.37	0.38	0.28	0.30	0.25	0.29	0.27	0.36	54.5*
S.D.	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.03	
HSD[a]			A,B	A	B	A	A,B		
Heel									
M	0.55	0.38	0.26	0.26	0.27	0.23	0.27	0.37	168.8*
S.D.	0.04	0.03	0.01	0.01	0.05	0.01	0.02	0.03	
HSD[a]		A	B	B	B	B	B	A	
Dynamic									
Forefoot									
M	0.18	0.22	0.13	0.18	0.14	0.18	0.19	0.18	71.3*
S.D.	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	
HSD[a]	A		B	A	B	A	A	A	
Heel									
M	0.11	0.17	0.16	0.13	0.14	0.17	0.14	0.18	39.3*
S.D.	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
HSD[a]		A	A	B	B	A	B	A	

[a] Means with the same letter were not significantly different ($p>.05$) on the Tukey HSD test.
* $p<.001$ on $df=7,24$.

Table B-18. Summary Statistics ($\underline{N}$=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Greasy" Cement

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
Static									
Forefoot									
M	0.25	0.27	0.19	0.28	0.18	0.21	0.22	0.25	35.7*
S.D.	0.03	0.02	0.03	0.02	0.01	0.01	0.01	0.02	
HSD[a]	A	A	B	A	B	B	B	A	
Heel									
M	0.21	0.19	0.22	0.21	0.29	0.20	0.19	0.25	10.9*
S.D.	0.02	0.04	0.04	0.03	0.02	0.04	0.02	0.07	
HSD[a]	A	A	A	A	B	A	A	B	
Dynamic									
Forefoot									
M	0.16	0.19	0.12	0.18	0.13	0.16	0.18	0.20	66.4*
S.D.	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	
HSD[a]	A	B	C	B	C	A	B	B	
Heel									
M	0.17	0.15	0.18	0.14	0.16	0.14	0.14	0.19	17.3*
S.D.	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	
HSD[a]	A	B,C	A	C	A,B	C	C	A	

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,24.

Table B-19. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Dry Grass

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				Static					
Forefoot									
M	0.57	0.80	0.74	0.80	0.82	0.74	0.70	0.60	174.9*
$S.D.$	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.03	
HSD[a]	A	B	C	B	B	C		A	
Heel									
M	0.68	0.73	0.74	0.89	0.89	0.77	0.82	0.60	222.3*
$S.D.$	0.01	0.02	0.01	0.01	0.02	0.02	0.01	0.01	
HSD[a]		A	A,B	C	C	B			
				Dynamic					
Forefoot									
M	0.40	0.67	0.68	0.76	0.74	0.71	0.68	0.58	239.2*
$S.D.$	0.01	0.02	0.01	0.01	0.01	0.02	0.03	0.02	
HSD[a]	A	B	B	C	C	B	B	A	
Heel									
M	0.55	0.60	0.68	0.71	0.78	0.71	0.77	0.57	165.2*
$S.D.$	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.02	
HSD[a]	A		B	B	C	B	C	A	

[a]Means with the same letter were not significantly different ($p>.05$) on the Tukey HSD test.
*$p<.001$ on df=7,24.

Table B-20. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Wet Grass

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.84	0.83	1.01	0.99	0.85	0.93	0.97	0.93	23.9*
S.D.	0.01	0.05	0.03	0.02	0.03	0.04	0.01	0.06	
HSD[a]	A	A	B	B	A	C	B	C	
Heel									
M	0.75	1.00	1.00	0.88	0.83	0.86	1.08	0.92	35.0*
S.D.	0.05	0.03	0.01	0.06	0.05	0.05	0.02	0.05	
HSD[a]		A	A	B	B	B		A	
					Dynamic				
Forefoot									
M	0.59	0.70	0.78	0.82	0.78	0.72	0.80	0.73	28.8*
S.D.	0.07	0.03	0.06	0.03	0.02	0.01	0.04	0.03	
HSD[a]		A	B,C	B	B,C	A,C	B	A,C	
Heel									
M	0.62	0.77	0.74	0.80	0.80	0.75	0.89	0.72	18.4*
S.D.	0.05	0.05	0.04	0.04	0.04	0.02	0.01	0.03	
HSD[a]		A,B	A,B	B	B	A,B		A	

[a]Means with the same letter were not significantly different ($p>.05$) on the Tukey HSD test.
*$p<.001$ on $df=7,24$.

Table B-21. Summary Statistics ($\underline{N}$=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Oily" Grass

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	$\underline{F}$
					Footwear				
					Static				
Forefoot									
$\underline{M}$	0.79	0.80	0.77	0.84	0.74	0.74	0.73	0.67	5.3^{*}
$\underline{S.D.}$	0.06	0.07	0.07	0.06	0.05	0.08	0.01	0.04	
$\underline{HSD}^{a}$	A,B	A,B	A,B	A	B	B	B	B	
Heel									
$\underline{M}$	0.67	0.97	0.78	0.68	0.77	0.67	0.80	0.67	18.7^{**}
$\underline{S.D.}$	0.06	0.10	0.10	0.07	0.07	0.04	0.02	0.04	
$\underline{HSD}^{a}$	A		B	A	A,B	A	B	A	
					Dynamic				
Forefoot									
$\underline{M}$	0.52	0.65	0.53	0.53	0.57	0.54	0.46	0.40	42.8^{**}
$\underline{S.D.}$	0.04	0.04	0.02	0.03	0.03	0.03	0.01	0.02	
$\underline{HSD}^{a}$	A		A	A	B	A,B	C	C	
Heel									
$\underline{M}$	0.56	0.68	0.50	0.57	0.69	0.50	0.60	0.41	81.5^{**}
$\underline{S.D.}$	0.02	0.02	0.04	0.02	0.05	0.02	0.01	0.04	
$\underline{HSD}^{a}$	A	B	C	A	B	C	A	C	

[a]Means with the same letter were not significantly different ($\underline{p}>.05$) on the Tukey <u>HSD</u> test.
$^{*}\underline{p}<.005$ on $\underline{df}$=7,24. $^{**}\underline{p}<.001$ on $\underline{df}$=7,24.

Table B-22. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Greasy" Grass

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.99	0.96	0.92	0.95	0.80	0.82	0.82	0.92	21.0*
$S.D.$	0.01	0.05	0.03	0.02	0.03	0.04	0.02	0.06	
HSD[a]	A	A	A	A	B	B	B	A	
Heel									
M	0.81	0.97	0.83	0.83	0.98	0.73	0.89	0.90	18.0*
$S.D.$	0.06	0.01	0.04	0.02	0.08	0.07	0.01	0.03	
HSD[a]	A,B	C	B	B	C	A	B	B,C	
					Dynamic				
Forefoot									
M	0.75	0.89	0.73	0.84	0.77	0.59	0.63	0.65	131.8*
$S.D.$	0.03	0.04	0.02	0.02	0.04	0.02	0.01	0.03	
HSD[a]	A	B	A	B	A	C	C	C	
Heel									
M	0.71	0.74	0.74	0.70	0.94	0.55	0.82	0.65	50.6*
$S.D.$	0.07	0.04	0.03	0.02	0.09	0.02	0.01	0.04	
HSD[a]	A	B	B	A				A	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,24.

Table B-23. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Dry Tile

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.69	0.76	0.79	0.75	0.93	0.98	0.73	1.00	30.6*
$S.D.$	0.01	0.05	0.03	0.02	0.03	0.04	0.02	0.06	
HSD[a]	A	B	B	B	C	C	A,B	C	
Heel									
M	0.50	0.60	0.84	0.99	0.87	0.86	0.65	1.01	70.8*
$S.D.$	0.08	0.06	0.05	0.05	0.06	0.06	0.02	0.08	
HSD[a]		A	B	C	B	B	A	C	
					Dynamic				
Forefoot									
M	0.63	0.65	0.64	0.67	0.83	0.77	0.51	0.87	32.5*
$S.D.$	0.03	0.03	0.01	0.09	0.03	0.04	0.01	0.01	
HSD[a]	A	A	A	A	B			B	
Heel									
M	0.41	0.54	0.72	0.82	0.71	0.62	0.56	0.88	81.3*
$S.D.$	0.04	0.04	0.04	0.03	0.03	0.07	0.01	0.07	
HSD[a]		A	B	C	B	A	A	C	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
*p<.001 on df=7,24.

Table B-24. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on Wet Tile

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
					Static				
Forefoot									
M	0.60	0.75	0.75	0.71	0.97	0.57	0.58	0.66	27.8*
$S.D.$	0.07	0.03	0.05	0.06	0.05	0.09	0.02	0.02	
HSD[a]	A	B	B	B		A	A	A,B	
Heel									
M	0.69	0.60	0.76	0.95	0.90	0.73	0.65	0.66	42.0*
$S.D.$	0.02	0.04	0.04	0.03	0.02	0.04	0.01	0.07	
HSD[a]	A,B	A	B	C	C	B	A	A	
					Dynamic				
Forefoot									
M	0.44	0.65	0.51	0.55	0.75	0.46	0.48	0.58	29.7*
$S.D.$	0.02	0.02	0.02	0.03	0.02	0.01	0.01	0.02	
HSD[a]	A	B	A,C	C		A	A	B,C	
Heel									
M	0.54	0.49	0.63	0.67	0.64	0.66	0.58	0.58	18.2*
$S.D.$	0.04	0.02	0.04	0.02	0.02	0.05	0.02	0.02	
HSD[a]	A	A	B,C	B	B,C	B	C	C	

[a] Means with the same letter were not significantly different (p>.05) on the Tukey HSD test.
* p<.001 on df=7,24.

Table B-25. Summary Statistics (*N*=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Oily" Tile

	Footwear								
Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	*F*
Static									
Forefoot									
M	0.34	0.32	0.27	0.28	0.19	0.27	0.24	0.38	49.3*
S.D.	0.03	0.02	0.01	0.02	0.01	0.02	0.02	0.03	
HSD[a]	A	A	B	B		B	B	A	
Heel									
M	0.56	0.33	0.22	0.30	0.28	0.23	0.29	0.38	173.9*
S.D.	0.05	0.02	0.02	0.01	0.03	0.02	0.02	0.03	
HSD[a]		A	B	A,C	C	B	C	A	
Dynamic									
Forefoot									
M	0.17	0.20	0.12	0.14	0.10	0.16	0.13	0.17	75.7*
S.D.	0.02	0.02	0.02	0.03	0.02	0.01	0.02	0.02	
HSD[a]	A		B,C	B	C	A	B	A	
Heel									
M	0.09	0.14	0.14	0.14	0.13	0.17	0.13	0.17	42.7*
S.D.	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	
HSD[a]		A	A	A	A	B	A	B	

[a]Means with the same letter were not significantly different (p>.05) on the Tukey *HSD* test.
*p<.001 on df=7,24.

Table B-26. Summary Statistics (N=4) and Results of Statistical Analyses for Coefficient of Friction (dimensionless) of Worn Footwear on "Greasy" Tile

Statistic	Combat Boot	Jungle Boot	Nike Air	Nike Train.	Red Wing	Reebok Pump	Rockport Hiking	Rockport Walking	F
				Static					
Forefoot									
M	0.26	0.26	0.15	0.25	0.21	0.24	0.23	0.34	25.8*
$S.D.$	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.02	
HSD[a]	A	A		A	B	A,B	A,B		
Heel									
M	0.19	0.22	0.25	0.21	0.22	0.23	0.24	0.34	10.4*
$S.D.$	0.01	0.02	0.01	0.01	0.02	0.04	0.01	0.03	
HSD[a]	A	B,D	C	A,D	B,D	B,C,D	B,C		
				Dynamic					
Forefoot									
M	0.21	0.17	0.08	0.15	0.16	0.17	0.19	0.27	105.3*
$S.D.$	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	
HSD[a]	A	B		B	B	B	B	A	
Heel									
M	0.14	0.16	0.18	0.16	0.16	0.16	0.13	0.27	30.8*
$S.D.$	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	
HSD[a]	A	A		A	A	A	A		

[a] Means with the same letter were not significantly different ($p>.05$) on the Tukey HSD test.
* $p<.001$ on df=7,24.